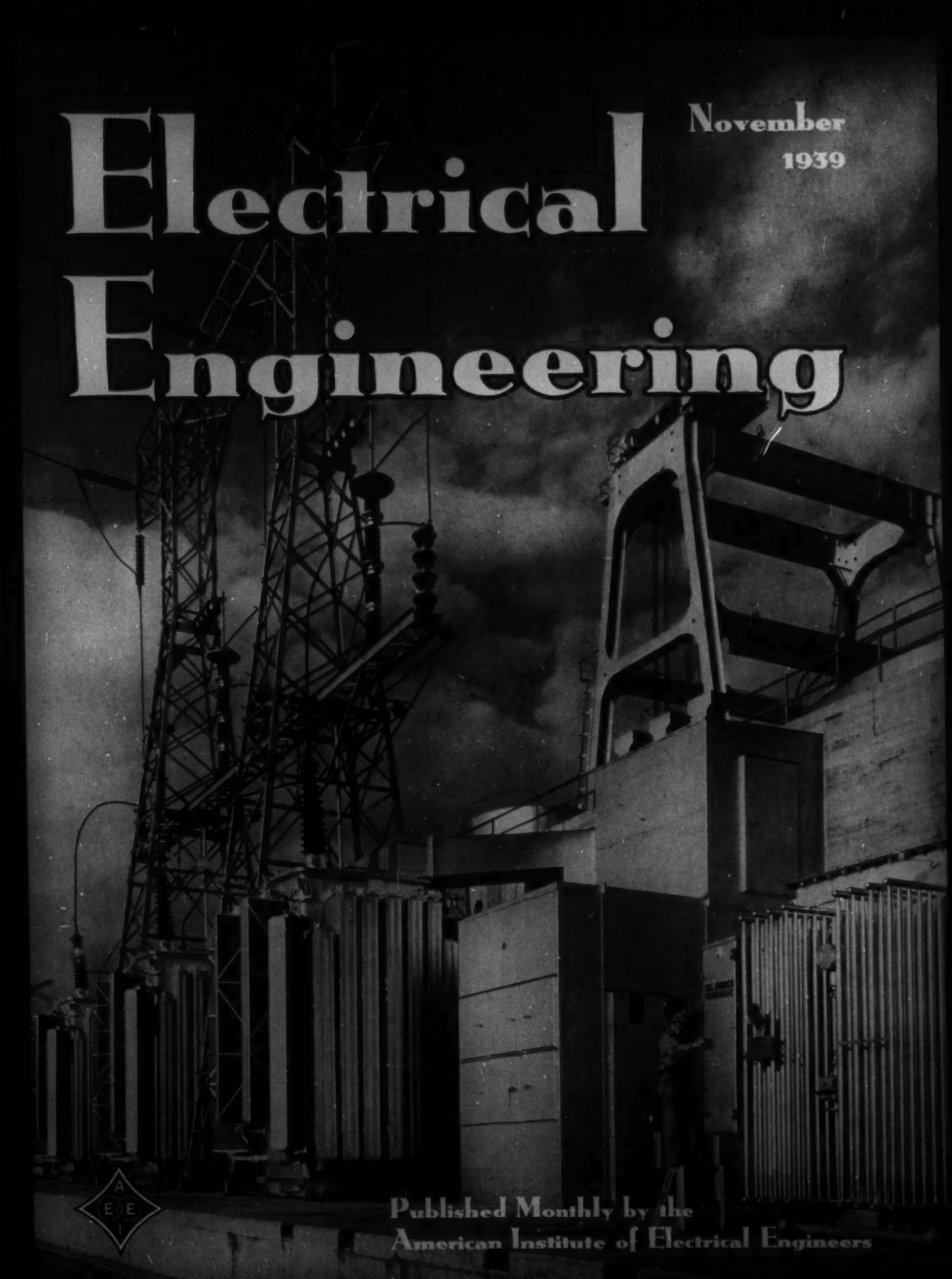
Electrical Engineering

November
1939



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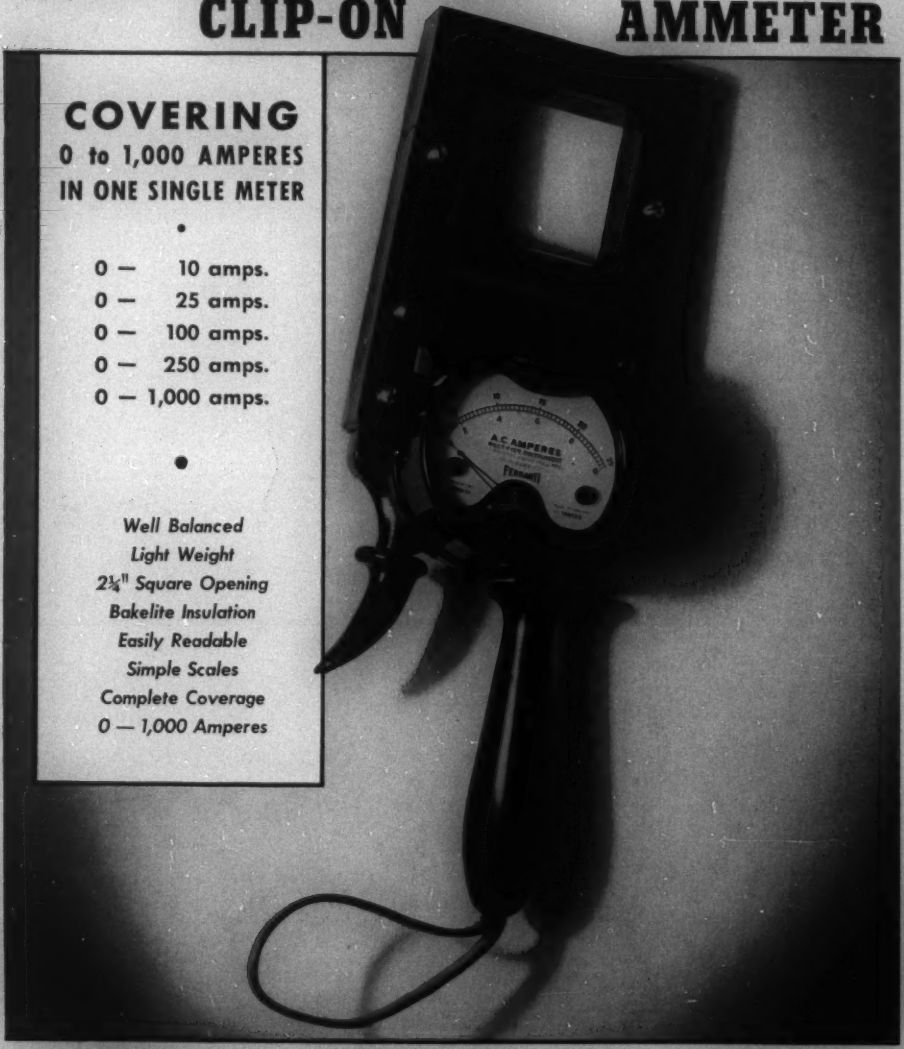

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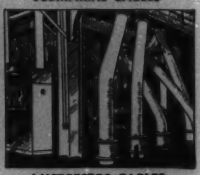

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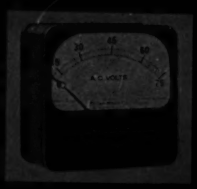

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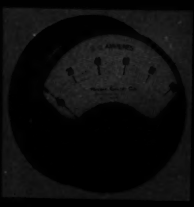

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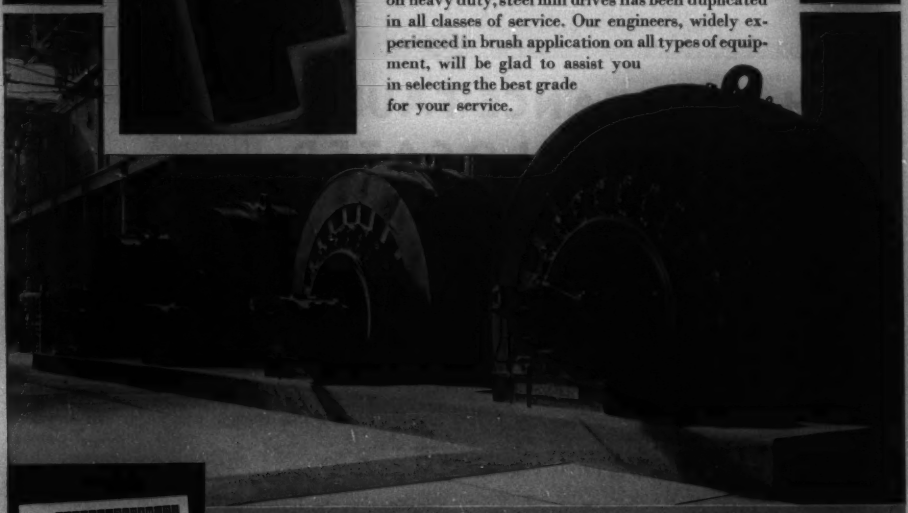

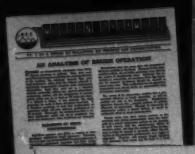

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VOLUME 58 NUMBER 11

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¶ Correspondence is invited on all controversial matters.

High Lights

Petersen Coil. The effectiveness of the Petersen coil in extinguishing line-to-ground arcs on a transmission system ordinarily is attributed to the fact that the current in the arc is kept at a low value. Another factor of perhaps greater importance is that characteristic of the Petersen-coil system which results in a very low rate of rise of recovery voltage across the arc terminals (*Transactions pages 576–81*). To reduce insulator flashovers on a 66-kv system, Petersen coils were chosen as the most practical method in the given situation; experience during the first year of operation shows that two-thirds of all faults were cleared without circuit-breaker operation (*Transactions pages 568–75*).

Nominations. Some members of the AIEE have remarked that its nomination and election procedure is "cut and dried" and that they have little if any voice in selecting the Institute's national officers. However, the Institute's by-laws contain provisions whereby the members, either individually or through their local Section organizations, may suggest nominees directly to the national nominating committee and other provisions whereby independent nominations may be made (*page 484*). On the facing page, President Farmer suggests some ways in which members may utilize the existing provisions to fuller advantage.

Measuring Watts and Vars. An instrument of negligible burden to measure watts and vars for use with a network analyzer has been built using an electrodynamic wattmeter, a negative-feedback vacuum-tube amplifier, and a phase-shifting network. The principle of instruments of this kind has other important applications in the field of electrical measurements (*Transactions pages 593–8*).

Vertical-Shaft Generators. Like other electrical machines, the design of vertical-shaft generators is complicated by interrelated electrical, mechanical, and thermal aspects and their usually conflicting requirements. The problem is further complicated by the fact that each machine must be "tailor made" to suit the requirements of individual hydroelectric projects (*pages 469–79*).

Emergency Ratings. Reduction of fixed costs of supply offers the major opportunity for improving the competitive position of electricity. One step in the solution of the problem is increased load ratings, mostly for cables. Maximum emergency loads should not affect the ability of the system to operate satisfactorily under extreme conditions (*Transactions pages 599–610*).

High-Speed Relaying. High-speed circuit breakers with operating times of eight cycles and one-cycle relays were introduced about 1930. Replies to a questionnaire circulated among typical operating companies revealed both satisfactory operation and some difficulties that were experienced in practical operation (*Transactions pages 588–92*).

Lightning Research. Various tests show that shattering, bursting, and explosive effects are caused largely by the high-current short-duration component of the lightning stroke, whereas fires, heavy fusion of metal, fulgurites, and extensive burning result largely from the low-current long-duration component (*pages 466–8*).

District Meetings. Reports of two AIEE District meetings, one held by the Great Lakes District at Minneapolis, Minn., and the other by the Middle Eastern District at Scranton, Pa., are included in the news section of this issue. Each meeting included a Student Branch convention (*pages 480–1 and 482–3*).

Rectifiers. By various means now available, the output of mercury-arc rectifiers may be regulated for flat voltage control, under- and overcompound voltage control, voltage control and current limiting, current control, and control suitable for other special applications (*Transactions pages 563–8*).

Electricity and Search for Oil. Electricity plays a vital part in several of the commonly used methods of locating deposits of oil hidden beneath the earth's surface. In addition to the strictly electrical methods, electricity provides the means of recording the results of other methods (*pages 455–62*).

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New Transmission Line. Simple and time-tested features form the basis of design of the recently completed 233-mile 220-kv line connecting the power plant at Boulder Dam with the Southern California Edison Company system (*pages 463–5*).

ECPD Meeting. At its seventh annual meeting, the Engineers' Council for Professional Development announced the accrediting of some 680 curricula in 140 engineering schools (*page 485*).

Mutual Induction. One of the causes of mysterious behavior of ground-current relays on parallel transmission lines is the induction of current in one line by a fault in the other line (*Transactions pages 582–8*).

Polarized Light. Increasing applications of polarized light in engineering are predicted in an article which reviews the nature and properties of the phenomenon (*pages 450–4*).

Hoover Medal. Joint engineering societies award, the Hoover Medal for 1939 will be presented to a prominent past-president of the AIEE (*pages 484–5, 489*).

Coming Soon: Among special articles and technical papers now undergoing preparation for early publication are: an article describing the unique conveyer that transported spectators through the General Motors "Futurama" at the New York World's Fair, by James Dunlop and W. T. White; an article reviewing operating performance of the low-voltage a-c network in Philadelphia, Pa., during the 12 years since it was established, by P. W. Crosby (A'27); an article outlining the present status of progress in electrical insulation achieved by physicists, chemists, and electrical engineers by L. J. Berberich (M'36); a paper on economical loading of high-voltage cables installed in underground subway systems by E. R. Thomas (M'30); a paper describing experience with ultrahigh-speed reclosing of high-voltage transmission lines by Philip Sporn (F'30) and C. A. Muller (M'36); a paper on ignitrons for the transportation industry by J. H. Cox (A'25) and G. F. Jones; a paper describing improvements in the construction of capacitor-type bushings by A. J. A. Peterson (M'30); a paper on line problems in the development of the 12-channel open-wire carrier system by L. M. Ilgenfritz (M'39), R. N. Hunter (A'39), and A. L. Whitman (M'30); a paper describing some applications of the type *J* carrier system by L. C. Starbird (M'35) and J. D. Mathis (A'28); a paper on out-of-step blocking and selective tripping with impedance relays by H. R. Vaughan (A'31) and E. C. Sawyer (A'39); and a paper on the dielectric strength of porcelain by P. L. Bellaschi (M'34) and M. L. Manning (A'36).

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A Message From the President

Membership Participation in AIEE Elections

THERE appears in this issue of ELECTRICAL ENGINEERING the usual annual notice inviting the membership to suggest to the national nominating committee candidates for the various national offices that will become vacant July 31 next. It recalls the comment occasionally heard that our elections of national officers are more or less "cut and dried," that the rank and file of the membership can have little influence in the selection of our officers, and that, as a consequence, our elections are not carried out in the completely democratic spirit contemplated by the prescribed procedure. A review of our election machinery therefore is opportune at this time.

Our procedure may be summarized briefly as follows:

1. The executive committee of each of the ten geographic Districts designates a member of the national nominating committee.

2. These ten members and five members of the board of directors chosen by the board constitute the official national nominating committee.

3. The membership at large, through a notice in ELECTRICAL ENGINEERING, is invited to suggest candidates for the various offices to the nominating committee.

4. The executive committee of each District in which the term of the vice-president is to expire makes the nomination for that office.

5. The nominating committee, at a meeting at headquarters, selects and recommends to the membership one candidate for each office to be filled, including in its list the names of the nominees for vice-presidents as selected by the District executive committees. The list of such names constitutes the official ballot upon which the members vote. (The nominating committee may designate more than one candidate, but to date that has never been done.)

6. Provision is made for the inclusion on the official ballot of the names of additional candidates, provided each such candidate is proposed by not less than 25 members. Thus opportunity is afforded for independent selections where there is any appreciable disagreement with those of the nominating committee.

It thus is assumed that 15 men qualified with respect to geographic distribution and knowledge of their fellow members are likely to make wiser selections in conference than could 17,000 men acting independently. This group is in a far better position to give consideration to and properly weigh the many factors that are involved in considering candidates, such as professional standing, technical or other contributions to the advancement of the art, service to the profession, service to the Institute, geographic distribution, and distribution with respect to the branches of the art.

This election machinery would appear to be adequate to obtain a reasonably wise selection of officers by a democratic process. It is very doubtful, however, if its provisions are being fully utilized to enlist the interest and aid of the greatest number of our members in the selection of candidates. Therefore, the following suggestions are offered:

1. That the executive committee in each *geographic District* invite the executive committee of each *Section* in the District to consider and recommend to the District executive committee:

(*a*). A candidate for the District representative on the national nominating committee—the recommendation to be accompanied by a brief statement of the qualifications of the proposed candidate.

(*b*). A suggested candidate (or candidates) for the presidency.

(*c*). In the vice-presidential election years, a suggested candidate (or candidates).

2. That the District executive committee, having before it the foregoing suggestions, consider them together with their individual suggestions and:

(*a*). Select a member of the national nominating committee (together with an alternate) to represent the District.

(*b*). Select a candidate for president whom the District representative on the nominating committee would be instructed to place in nomination at the meeting of the nominating committee.

(*c*). In vice-presidential election years, nominate a vice-president for the District.

3. That more members respond to the invitation to submit individual suggestions directly to the national nominating committee.

Compliance with these suggestions would enlist the interest of a greater number of members in the election procedure which in itself is much to be desired. A further and more important result would be that the 15 members of the national nominating committee, functioning as judges on behalf of our 17,000 members in the selection of candidates for the national offices, would have before them a larger number of suggested candidates. It is only reasonable to conclude that the greater the number of proposals considered, the wiser is the committee's final selection likely to be, particularly when many of them are already the considered selections of other groups.

F. Malcolm Farmer

Polarized Light

L. W. CHUBB
FELLOW AIEE

With the development of practical polarizing sheets, polarized light, long known and employed by science, is being given increasingly wide use in engineering and industry. Its applications in the study of stresses, in photography, stereoscopic motion pictures, vehicle lighting, and display lighting, are among those mentioned by this author, who reviews polarized light for the engineer.

POLARIZED light was discovered in the 17th century by Huygens and has been intensively studied and used in scientific work. Engineers, however, seem to remember little about the polarized light studied in high-school or college physics, and infrequent engineering application or use is made of it. The object of this article is to refresh the memory of the engineers with respect to polarized light, by describing in a simple engineering way its nature, properties, and uses.

Nature of Light

The nature of light has been a speculative and controversial subject among philosophers for centuries. Experimental evidence has caused the prevailing theory of the nature of light to change back and forth at least four times between a corpuscular emission and a wave phenomenon in an imaginary elastic medium, which we call the ether. There have always been some experimental facts which could not be satisfactorily explained by either theory. Today, the physicist seems resigned to the corpuscular nature of light, although certain difficulties still exist. The modern physical theories, involving quantum mechanics and relativity, teach us that light may be assumed to consist of a myriad of projectiles which we call photons or quanta of gamma radiation. They travel through space at a constant velocity.

Since a flux of either light particles or vibrations in the ether can be shown to have the characteristics of waves, we may more easily treat the subject as wave phenomena just as we treat electrical phenomena as waves even though we know that an electrical current consists of charged corpuscles of electricity—electrons and ions.

Kinds of Wave Motion

There are different types of wave motions which are readily recognized. In the first place, there are longitudinal waves, such as sound waves through gases, liquids, or solids, in which the medium vibrates to and fro in the direction of propagation. Because of the elastic characteristics of the medium, waves of compression and rarefaction travel away from the sources at a speed dependent upon the elasticity and the density of the medium.

Based on a demonstration talk given before the AIEE New York Section, New York, N. Y., March 9, 1937, under the auspices of the AIEE committee on production and application of light.

L. W. Chubb is director of research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Second, we have surface waves, such as those on deep water, in which the particle of the medium moves in a circle as the waves progress. At the crest of the wave, the water moves forward; as the wave passes, the water falls; in the trough, it is moving backward; and as the next crest approaches, it rises and moves forward again. In this case, we do not depend upon the elasticity of the medium but upon its density and forces of restitution.

The third familiar wave is what is called a transverse wave, in which the particles of the transmitting medium vibrate at right angles to the direction of propagation. If we shake the end of a stretched rope or wire, waves will be propagated along it by the transverse motion of the flexible yet inextensible rope. Light, radio, heat, and all other invisible waves which make up the complete electromagnetic radiation spectrum may be explained by this type of wave with transverse vibrations.

Many of the phenomena of light can be explained by the first form of longitudinal wave in an elastic medium; however, the transverse vibrations must be assumed to explain all phenomena, especially those dealing with polarized light. It was the discovery of the "one-sidedness" of polarized light which pointed the way to the transverse-wave theory for light.

Properties of Light

Light (including heat, radio, and the invisible radiations in the complete spectrum) has many interesting properties. Its wave frequency determines its color in the visible spectrum (other properties in the invisible ranges). All such waves of different frequency can be combined, separated, transmitted quite independently in crisscross fashion in homogeneous space, without any interference. They may be refracted, reflected, transformed, absorbed, have their speed and phase changed, made to interfere under certain conditions. Besides being the means by which we see, light is essential in many ways. It makes the vegetation grow and produces photochemical and thermal changes. It is the primary cause of the winds, the rain, the ocean waves, and the carrier of all direct and stored energy from the sun to the earth.

Forms of Polarized Light

There is a difference between ordinary light and polarized light. In ordinary light, the transverse vibrations are random or change angle or azimuth very rapidly.

On the other hand, polarized light may be said to consist of transverse-wave vibrations in which there is some regular motion.

There are three typical forms of polarized light: plane-polarized light, elliptically polarized light, and circularly polarized light.

Let us return to our horizontal stretched rope to illustrate these forms of waves. If we shake the free end of the rope transversely up and down, crosswise, and at all diagonal angles, waves of an irregular form will be propagated along the rope and illustrate the random nature of ordinary light. If next we shake the free end of the rope up and down, the waves propagated along the rope will be in a vertical plane and illustrate the plane-polarized waves. Elliptically and circularly polarized waves may be illustrated by shaking the free end in an elliptical or circular path respectively, propagating regular waves along the length of the rope. Each particle of the rope will describe a plane, ellipse, or circle as the case may be, but successive parts will have different time phase.

One may question whether the circular motion of the rope is a transverse vibration. Let us answer this by saying that the motion can be resolved into two linear transverse vibrations at right angles and in quarter-space phase. This method of resolving the wave motions into two vibrations at right angles is familiar to the engineer and will be of help in understanding what is to follow.

We may therefore reconsider the examples given, stating them in what we may call vertical and horizontal polyphase components. Plane waves are produced by a vertical and horizontal vibration of the same frequency and in time phase. The azimuth of the combined linear motion depends upon the relative amplitude of the two components. Elliptical waves are produced by the combination of vertical and horizontal vibrations of the same frequency and different in phase. Circular waves result from vertical and horizontal motions of the same frequency, equal amplitude, and in quadrature time phase. These relations combining quadrature harmonic motions are so well understood by engineers that no diagrammatic illustration is considered necessary.

Our single rope might be said to represent a single ray of light. To visualize a pencil of rays a great many parallel ropes should be assumed and the waves propagated along all of them together by the simultaneous transverse motion of their free ends.

In an electrical circuit, currents of different frequencies and phases may be simultaneously transmitted. The same is true of light, and we may suppose each of the vertical and horizontal component vibrations to consist of different frequencies to represent the different color components.

Methods of Polarizing Light

It has been pointed out that common light vibrates randomly at all azimuths, transverse to the direction of propagation. To plane-polarize light, it is necessary, then, in some way to resolve all the component vibrations into one plane. With the rope, suppose it extends between two pickets of a fence, so that it can move only vertically. Any irregular motion given to the rope will be propagated to the fence and only the vertical components of the motion will proceed beyond the fence. We may then say that the waves beyond the fence are plane-polarized.

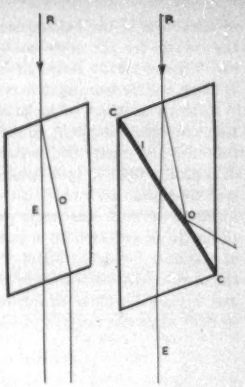


Figure 1 (left). Diagram of a crystal of Iceland spar in section

Figure 2 (right). Diagram of the Nicol prism, the commonest means of polarizing light by double refraction

There are several ways of polarizing light to get the necessary regular motion of vibration.

Crystals with their atomic lattice are like the picket fence, but, instead of allowing vibrations in one plane only, the most common crystals will allow transverse vibrations to pass through in planes parallel to and at right angles to the optic axis, or in the direction of the atomic lattice rows. Beyond the crystal, or birefringent material, as it is called, the two quadrature wave components will combine vectorially again and proceed as before.

Certain crystals, of which tourmaline is a good example, transmit the two vibrations with unequal absorption. One ray is strongly absorbed and the other transmitted quite freely. With a suitable thickness of tourmaline crystal, we may substantially absorb one vibration and the transmitted light will be plane-polarized.

This then is one way to plane-polarize light, by differential absorption in a dichroic crystal.

Certain organic crystals, such as iodo-sulphate of quinine, have this property of absorbing one vibration much more strongly than does tourmaline. A thickness of 0.0002 inch will give practically complete polarization of visible light. Certain other crystals, known as double-refracting crystals, such as calcite or Iceland spar, have the property of refracting the component vibrations differently so that they may be separated.

Figure 1 shows a crystal of Iceland spar in section. When a ray of common light R is transmitted into such a crystal, two refracted beams O and E arise. They are both plane-polarized and their planes of polarization are at right angles to each other. If one of these rays can be discarded, the transmitted light will be plane-polarized.

Figure 2 shows the Nicol prism, the most common means of polarizing light by double refraction. The crystal is cut along the line CC; the faces polished and cemented together again with Canada balsam. The index

of refraction of the balsam being lower than the index of the crystal for the more oblique ray O, it will cause the ray O to be totally reflected and thus rejected. The ray E alone will be transmitted as plane-polarized light.

A third method of polarizing light is by reflection. Light obliquely incident on a transparent surface is partly reflected and partly transmitted. In figure 3, the ray SO of common light is split into a reflected beam OR, and a refracted beam OT, which is transmitted. As the angle of incidence θ and the angle of refraction ϕ are varied, the ratio of reflected to transmitted light increases until at glancing incidence all of the light is reflected. Also, the component vibrations in the reflected light normal to and within the plane of incidence (ROS) change in ratio so that when the tangent of the angle of incidence ($\tan \theta$)

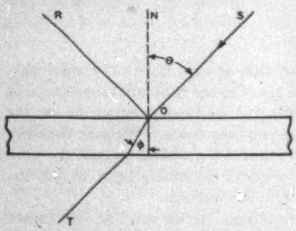


Figure 3. Diagram showing how light can be polarized by reflection on a transparent surface

is equal to the index of refraction of the reflecting substance, substantially all of the reflected light is vibrating in a plane normal to the plane of incidence.

Figure 4 shows the light reflected from a polished glass surface. Curve A shows the percentage of the reflected-light components vibrating normal to the plane of incidence and curve B shows the percentage of reflected-light components vibrating in the plane of incidence, for a reflecting surface having an index of refraction of 1.5. It will be noted that all components vibrating in the plane of incidence substantially vanish at 56 degrees, so that at this angle we have plane-polarized light reflected. This critical angle, called Brewster's angle, is the one for which the tangent is equal to the index of refraction.

It will be noted that only 15 per cent of the light vibrating in the one plane is reflected at the critical angle. Since only half of the intensity of common light is due to components vibrating in this plane, the useful polarized light from a single surface amounts to only 7.5 per cent of the incident light. To overcome this limitation, it is customary to use multiple plates of glass in order to obtain reflections from the front and back surfaces of each.

These are the three most common means of plane-polarizing light; however, there are others, one of which may be mentioned. Very small particles in scattering light give a predominance of polarized light at right angles to the incident beam. Thus the ring of blue sky in direction normal to the direction of the sun's ray is almost completely plane-polarized. Also the rainbow is polarized.

Before showing how elliptically and circularly polarized light are produced, it is well to call attention to certain simple conventions and recall some facts about light and optics. By convention, the plane of polarization is at right angles to the direction of vibration of the polarized light. When a ray strikes a surface, the angle of incidence is equal to the angle of reflection. When a ray of light passes from a less dense medium (air) into a more dense medium such as glass, the refracted ray in the glass is turned toward the normal (see figure 3). The index of refraction is the ratio of the sine of the angle of incidence to the sine of the angle of refraction. In figure 2

$$\text{Index of refraction} = \frac{\sin \theta}{\sin \phi}$$

Light waves are retarded or slowed in velocity in dense media. The wave velocity is the velocity in space divided by the index of refraction of the given substance. This means that the slower waves (at the same frequency) must have a correspondingly shorter wave length.

Crystals and certain transparent substances with a grain, such as cellophane, have different indices of refraction for vibrations normal to and parallel to the axis or grain of the material. (Some crystals known as biaxial have three indices.)

Just as currents of equal frequency and different phase must be added vectorially, the vibrations of light of different space and time phase must be treated vectorially.

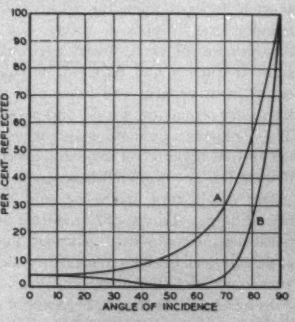
Intensity of light is proportional to the square of the amplitude of vibration, just as energy dissipated in a conductor is proportional to the square of the current.

Assuming all light vibrations resolved to two components at right angles, the foregoing considerations make it simple to understand the production and properties of circularly and elliptically polarized light.

Figure 4. Graph indicating reflection of light from a polished glass surface, index of refraction, 1.5

Curve A—Reflected-light components vibrating normal to plane of incidence

Curve B—Reflected-light components vibrating in plane of incidence



Instead of a rope having a round section and an equal flexibility in all directions, suppose we assume a stretched wire of rectangular section, with the greater dimension vertical and the wire so long that there will be no waves reflected back from the fixed end. If we shake the free end up and down, there will be greater stiffness and the vertical waves will travel faster than if we shake it horizontally. Suppose now we shake the end at constant frequency, diagonally at 45 degrees. This is the same as a simultaneous vertical and horizontal vibration of

equal amplitude. At the hand the motion will be a line, both vertical and horizontal motions in the same time phase. As we proceed along the wire, the horizontal components of vibrations, due to their slower velocity, will lose in time phase and the transverse motion of the wire will become an ever-widening ellipse, until the point along the wire is reached where the horizontal waves have lost just a quarter of a cycle. Here the wire will be found to be describing a circular path. Further change in phase will result in an elliptical motion with its major axis in the other diagonal and when the phase difference is one-half cycle, the motion will again be a straight diagonal line at right angles to the linear motion of the hand. At three-fourths-phase difference, the circular motion will again appear, but the direction of rotation will be opposite to that at the quarter-wave position.

Figure 5 shows graphically the path of the wire in a plane normal to the wire. There are, of course, many individual wave crests between these points along the wire where the particular phase differences exist.

Now since some crystals and other birefringent materials have different indices of refraction and different speed of wave propagation in planes perpendicular and parallel to the optic axes, this same phase difference between the right angle component vibrations can be obtained and plane-polarized light readily changed to circular or any form of elliptical polarization.

If plane-polarized light is normally incident upon a crystal plate and the transverse vibrations of the light are parallel to or at right angles to the optical axis of the crystal, the light will be transmitted and emerge as plane-

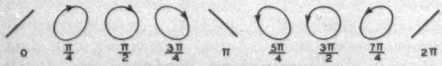


Figure 5. Diagram of vibrations of a stretched wire of rectangular section, shaken diagonally at 45 degrees in constant frequency

polarized light in the same azimuth. It will suffer only certain phase retardation depending upon the thickness and index of refraction.

If now the transverse vibrations of the incident plane-polarized light enter the plate at an azimuth of 45 degrees, they will be split into two components vibrating parallel to and at right angles to the axis.

These components will be of equal amplitude, but since they will travel at different velocity, there will be progressive difference in phase. If the thickness of the crystal is such that the relative retardation is just one-fourth cycle, they will emerge into the homogeneous medium, air, as circularly polarized light. This is what is called a quarter-wave plate, and is used to convert plane-polarized to circularly polarized light.

To go further, suppose the plate to be twice as thick so that it produces one-half cycle of relative retardation; it will be a half wave plate and the light will emerge as plane-polarized light shifted 90 degrees in azimuth.

It is evident that for intermediate thicknesses elliptically polarized light will be produced.

This consideration of retardation of a single frequency or wave length seems simple enough, however, for other wave lengths the relative phase retardation will be quite different for the same thickness. What is a true quarter-wave plate for yellow light, for instance, will not be a quarter-wave plate for red or blue. Other means involving internal reflection, such as Fresnel's rhomb, must be used when working with white or mixed light, in order to obtain equal phase shift for all wave lengths.

Properties and Uses of Polarized Light

From the foregoing it is evident that light passing through a polarizer will have its vibrations changed to parallel planes and this light will readily pass on through another polarizer which is similarly oriented, or said to be optically coincident. If now the second polarizer is rotated around the beam as an axis, the component of light passing through will be proportional to the cosine of the angle of rotation, and when it has rotated 90 degrees, all of the light will be cut off. Since light intensity is proportional to the square of the amplitude of vibration, the intensity will vary as cosine square giving a variation of transmitted intensity, as shown in figure 6.

This feature is of great value in the use of polarized light and is the means by which we may test for any rotation of the plane of polarization or may sort out selectively different color components which may be polarized in different planes.

Polarized light is rotated by certain substances. Thus a sugar solution will rotate the plane in proportion to the strength of the solution and the length of path traversed. This is called *specific rotation*.

Polarized light is also rotated in other substances when a magnetic field traverses the substance in the direction of the passage of light. This is called *magnetooptic rotation*, and although not generally used, has many possible uses now that practical polarizing sheets have been made available.

Still other substances traversed by polarized light become more or less birefringent when subjected to electrical stress. This is called *Kerr effect* and may be used for light valves, to modulate a beam of light in proportion to a voltage wave.

Solid transparent and optically inactive substances,

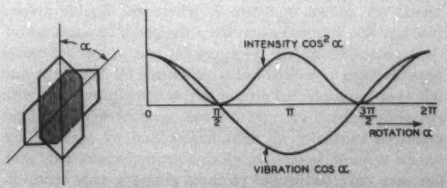


Figure 6. Diagram showing variation in intensity of a beam of polarized light transmitted through a second polarizer which is rotated around the beam as an axis

such as glass, celluloid, and bakelite, when subjected to stress obtain birefringence; and with polarized light, enable one to tell by the fringes which appear the stress conditions in the material. This is called *photoelasticity* and is most valuable in working out stress problems, using transparent models, which have the same shape and load distribution as the machine part or structure which is under stress analysis. The same phenomenon shows the internal stresses in improperly annealed glass products.

It was shown in connection with figures 3 and 4 that reflected light from a smooth surface is strongly polarized. This glancing-off light is what is called specular reflection or glare; it has the color characteristics of the original source rather than those of the reflecting surface. Instead of helping us to see the object from which it is reflected, it interferes with vision.

Figure 3 illustrated the reflected and transmitted ray for a transparent surface. When we have an opaque surface (let us assume a blue china plate), the specularly reflected light glances off by showing shine, glare, and high lights characteristic of the source of light. Thus the high lights produced by the reflected image of the window or electric lamp are white, not blue. The vibrations that are refracted into the surface go to illuminate the substance. They are partly absorbed and partly reflected as scattered light and it is by these components that we discern the object—its true color, texture, and so on.

The glare which is polarized can be effectively eliminated by observing the object through a polarizer properly oriented. With polarizing spectacles, this is the secret of the selective reduction of glare and shine without a similar reduction in the scattered radiation by which we see.

In photography, polarizers may be used before the camera lens to filter out the sky glare which is polarized, and get other artistic effects. In studio work, the objects may be illuminated by polarized light and the camera lens covered by a polarizer at quadrature azimuth, thus eliminating all disagreeable high lights and giving photographs that require no retouching for reproduction.

Another promising use of polarized light is in vehicle lighting. If all cars project polarized light vibrating in a plane 45 degrees to the horizontal and the road is viewed through a polarizing screen that is optically coincident, it is possible to see the reflected light from your own headlights, but there will be no glare from opposing lights similarly equipped. The opposing lights will be optically crossed with your viewer, because the opposing car is traveling in the opposite direction. The arrangements are shown in figure 7, where the double arrows indicate the diagonal azimuth of the plane of polarization.

Stereoscopic motion pictures in true color are made possible with polarized light. Pictures for the right and left eyes are projected alternately or simultaneously, with polarized light. Pictures for the separate eyes use light polarized mutually at right angles and by viewing the screen through polarizing glasses properly oriented, each eye sees only its proper picture, giving a true three-dimensional effect.

Polarized light of two or more colors polarized in different azimuths may be mixed and selectively sorted out, so as to give advertising signs and display devices of various color combinations. It may be used for secret signaling and telephonic communication through a beam of light, and in many ways for control and position indication.

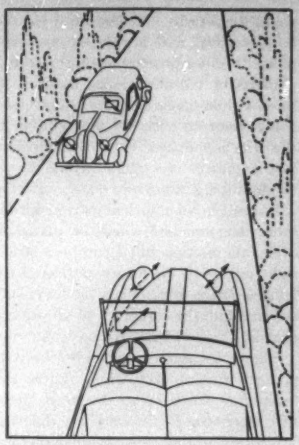


Figure 7. Diagram illustrating the use of polarized light for motor headlights

In the past very little engineering application has been made of polarized light because efficient polarizers of large aperture were not available. In recent years, however, absorption polarizers in sheet form have been developed and provide a means by which the engineer may make use of the many unique properties of polarized light.

Illumination Notes*

Light and Safety. Records kept by L. J. Samson, city traffic engineer of Chicago, Ill., show a large dividend in safety on the investment for lighting dangerous intersections with sodium-vapor lamps. For the year following the installation of the lamps, in November 1937, as compared with the preceding year, night accidents dropped from 95 to 40, or 58 per cent; the number of persons injured from 43 to 14, or 67 per cent; and property-damage collisions from 61 to 28, or 54 per cent.

A recent report by E. R. Sherbaum, electrical engineer, New Jersey State Highway Department, shows that for the first 11 months of 1938, on highways where modern lighting systems had been installed, fatalities from night driving decreased 37 per cent (from 245 to 154) as compared with the same months in 1937. On those same highways, the number of fatalities from daytime accidents remained constant (136 as against 137). In counties where lighting installations are not completed, the fatalities from night accidents also remained practically constant (23 as against 22).

*Contributed for the AIEE committee on production and application of light by L. A. Hawkins (A'03, M'13) executive engineer, research laboratory, General Electric Company, Schenectady, N. Y.

Electricity Aids in the Search for Oil

DANIEL SILVERMAN
ASSOCIATE AIEE

The apparent magic that created great oil fields out of grassy marshlands is not a product of the divining rod but the result of the application of scientific principles involving the fundamentals of the science of applied geophysics. A review of the various methods of geophysical prospecting for oil, in which electricity has played a large part, is presented here. In addition to strictly electrical methods, electrical measurements provide a means of recording the results of other methods.

EVER since man has made use of the earth's mineral products, the thought has been in his mind that it should be possible to predict, by some means or other, the location of mineral deposits hidden from view. In olden days such possibilities were placed altogether in the realm of magic, although even today, the divining rod is thought by some to possess the supernatural faculty of locating all kinds of mineral deposits. The apparent magic that created the great oil fields that rise so suddenly out of grassy marshlands, where no surface indication hinted at their presence, is not one of the divining rod, but goes far into the realms of mathematics, physics, and astronomy. It involves the foundations of the science of applied geophysics.

Applied geophysics deals with the measurement of the various physical properties of the rocks of the earth, both on and below the surface, as these properties exhibit differences from place to place. Any means of detecting these minute differences in physical properties will tell something of the actual subsurface structure of the rocks themselves. It is the purpose of this article to describe the many ways in which scientific principles have been applied to this study of the physical properties of the surface of the earth. No attempt will be made to evaluate the various methods, but simply to describe the many ways in which the geophysicist has made use of old principles in this modern work.

The modern search for oil is based on the anticlinal theory, which states that if oil, gas, and water occur in bedded sands or sandstones, and the formation is uplifted into a closed upfold, anticline, or dome, as shown in figure 1, the oil, gas, and water will accumulate in distinct horizons in the sand body according to the specific gravity of each. This will tend to permit the oil to segregate itself into commercially recoverable quantities. The search for this type of formation was first carried on by the geologist

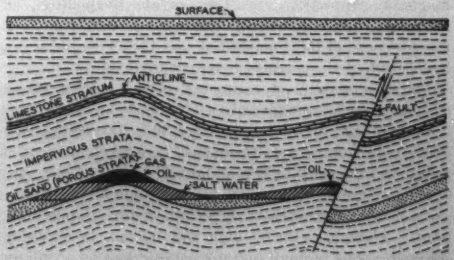


Figure 1. Diagram of typical geological structures, showing how oil and gas may be trapped

Essential substance of a lecture delivered at a meeting of the AIEE Tulsa Section, Tulsa, Okla., March 20, 1939.

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Figure 2. A magnetometer in field use

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on the basis of surface indication alone. However, it soon became evident that such formations could and did exist below the broad flat plains of the Gulf Coast region, and the use of methods that would probe below the surface became necessary.

The first attempt was to apply all known physical principles to the search. This naturally tended to the use of gravity forces, earth magnetism, electrical properties, seismic velocities, and radioactivity. These branches of physics are still the mainstay of geophysics, although some branches are less so than others. For gravity work the torsion balance, gravity meter, and the pendulum are used. In seismic work the refraction and reflection methods have shared the interest of the field. For magnetic measurements, the magnetometer, the magnetic variometer, and the earth inductor have been used. In the electrical field, resistivity measurements, transient-response measurements, the selective absorption and reflection of a-c fields, and radio waves, have been used for surface study, and resistivity and self-potential studies for well work.

Magnetic Methods

In applied geophysics, the use of magnetic principles is based upon the fact that different kinds of rocks, both on the surface and under the surface, will exhibit different magnetic properties, and thus create inequalities, or anomalies, in the normal earth's magnetic field. The measurement of these anomalies, and their interpretation, is the work of the magnetometer geophysicist.

Magnetic values appearing on maps showing oil or mineral prospects are given in units called gammas. This is a unit of field strength and is equal to 1/100,000 part of a gauss. For comparison, the normal vertical component of the earth's magnetic field is about 0.25 gauss. Lines connecting all points of the same gamma value are called isogams and appear much as structural or topographic contours. Thus a magnetic high will appear as so many gammas above normal, and a magnetic low as so many gammas below normal. These values are normally given for the vertical component of magnetic field intensity, because the interest of the geophysicist is generally applied to the magnetic properties of subsurface formations.

The group of instruments used for magnetic surveys, includes: the magnetometer and dip circle, which are used to measure the *direction* of the earth's magnetic field at any point; the vertical and horizontal variometers, which are used to measure the *change in magnetic field strength* from point to point; and the earth inductor, which gives a measure of the *total field strength*.

For use when the magnetic anomalies are small, such as those found over salt domes containing a small amount of disseminated magnetite or other magnetic ore, very sensitive and delicate types of variometers, similar to that shown in figure 2, have been developed which will read to one gamma. However, with such sensitivity, there are present many disturbing forces, for which accurate corrections are necessary. The general shifting of magnetic intensity over a period of years, the diurnal changes, the effects of temperature variations, and the changes due to magnetic storms, are the major sources of error.

In recent years, some basis has been found for changing the basic assumptions for the interpretation of magnetic anomalies. In former years it was thought that all magnetic anomalies were caused by a basement of shallow igneous or metamorphic rocks. Today it is believed that sufficient difference in the magnetic susceptibility exists in the sedimentary deposits to produce noticeable magnetic anomalies. Especially is this true in the Gulf Coast and in California where the basement is buried beneath a four- or six-mile-thick blanket of sediments. Since magnetic anomalies are observed, it stands to reason that they must originate with the shallower sediments.

Gravity Methods

The principle of operation of the gravimetric instruments is the universal law of gravitation which specifies that between any two masses there is a force of attraction dependent upon the product of their masses, and inversely proportional to the square of the distance between them. The value of these instruments in the search for oil is based upon the fact that the presence of oil is often associated with the presence of certain structures, some of which provide space-mass relationships that are susceptible of recognition by gravitational-force measuring instruments.

The two main types of gravimetric instruments, the gravimeter and the torsion balance, differ in their operation to the extent that the gravimeter measures the *force of gravity* at any point, while the torsion balance measures the horizontal *gradient of gravity;* that is, it measures the amount by which the force of gravity varies from one point to an adjacent point. Both of these instruments are affected by the gravitational force field, and are thus affected by near masses and those at a distance. By virtue of the inverse-square law, the distant ones are less effective, and there is thus a practical limit in the working depth of a gravity instrument. Furthermore, since all mass within the range of the instrument affects its indication, a given reading may be due to a small mass close to the surface, or to a large mass at some depth.

The gravimeter is sensitive only to the vertical component of gravitational force. Consequently it is not affected appreciably by surface structure. However, the torsion balance, since it measures horizontal change in the force of gravity, is sensitive to horizontal forces, and consequently is at a disadvantage where there are more major variations in level of the surface of the ground, even at considerable distances from the instrument.

The torsion balance, as its name implies, is an instrument in which the unbalance in two forces of attraction, for two ball masses suspended from a horizontal bar, is balanced by means of the torsion in a fiber by which the bar is hung. The two masses are horizontally displaced by equal amounts on opposite sides of the point of support of the fiber, and the horizontal elevation of one is less than the other by an amount roughly equal to their horizontal displacement. Thus, for masses below and to the side of the instrument, there is a difference in force on the two masses due to the different distances of the balls from the mass. It is this small differential force that is measured by the instrument.

Figure 3 shows a torsion balance in process of being set up at a station. A special type of housing is necessary to protect it from atmospheric or physical disturbances during the recording period.

The units of measurement used in applied gravity prospecting are the milligal and the eötvös. The milligal is the unit of measurement of the intensity of gravity represented by an acceleration of 1/1,000 centimeter per second per second, and is about equal to the one-millionth part of gravity at sea level. The eötvös is the unit of measurement of the gradient, or variation of gravity per centimeter, and is represented by 10^{-9} gals per centimeter (centimeters per second per second per centimeter). Since one gal is approximately 10^{-3} gravity, one eötvös is approximately represented by a change in gravity of one part in 10^{12} per horizontal centimeter of distance.

Figure 3. A torsion balance in carrying position

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The gravimeter and pendulum measure the vertical component of gravity. Since the period of oscillation of a pendulum is dependent upon the acceleration of gravity, the pendulum can be used as a gravimetric instrument. The field practice consists of the measurement of the variation in period of the pendulum as it is moved from point to point. These variations are observed by comparison with the period of a similar pendulum at a base station.

In the gravimeter, measurement is made of the change in position of a spring-supported mass under the effect of the gravitational field. The best gravimeters are sensitive to about one 10,000,000th part of gravity or less. This extreme sensitivity makes them responsive to small buoyant forces resulting from a change in barometric pressure acting on the mass, to small air currents caused by temperature changes, and to the change in spring constant of the suspensions with temperature. They are generally built in thermally insulated cases, with accurate thermostatic control of the temperature. Figure 4 shows one type of gravimeter for swamp work.

Core-Analysis Methods

Since the time when all surface indications of oil were investigated, and it was found necessary to go into the earth for information, one of the earliest and simplest methods was to drill. One step beyond the driller's log is the core log, and the record provided by the proper analysis of the cores recovered. Cores may be examined for water- and oil-bearing sands in strata too thin to register on the recording instruments of electrical devices.

The core drill uses a special type of bit that, while progressing down through the sediments, cuts away all but a small central cylinder which is left intact. This is carried in a central core cylinder or barrel, which is brought to the surface, and the core recovered. Core drills are of two main types: those that require removal of the drill stem from the hole, and the substitution of a core bit in place of a regular drill bit; and those of the so-called wire line type. These involve the use of a special bit and a core barrel which is introduced into the bit, and withdrawn from the bit, through the inside of the drill stem.

Core analysis is advanced to the point where it is an extremely important part of the total plan of prospecting. Chemical and physical analyses have been developed for the determination of the physical properties of the cores, and to indicate the value of porosity, the permeability of the sample to gases or liquids, and the percentage content of water and oil. These are extremely important to the oil operator. Additional information for the exploration department is available from further analysis of the core. This is in regard to the depth to certain strata, and the dips of the various planes of the strata composing the core. In other words, knowing the orientation of the core, and measuring the angle of inclination of the beds, the dip and strike of the various beds through which the well passes can be calculated. This information is extremely important in correlation work.

There are several different ways of obtaining this infor-

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Figure 4. A modern light-weight high-sensitivity gravimeter for swamp work

mation. One is to take a record of the orientation and inclination of the core barrel in the hole at the time that the core is being pulled. The other is a magnetic method of core analysis by which it is possible to measure the very small magnetic induction from the core itself, and align it with the known direction of the resultant earth magnetic field at the point. When these are aligned, the dip and strike of the beds can be determined. This magnetic effect depends upon the presence of minute quantities of magnetically susceptible material deposited in the sediments composing the stratum.

In a recently proposed method, the magnetic materials in the core are arbitrarily increased by injecting into the sediments at the base of the well, before the core is cut, a liquid jell containing minute magnetic particles. These particles are oriented in the earth's field and are bound in this position by the solidification of the jell. Upon cutting the core, a positive magnetization is observed, on the basis of which the core is oriented.

Soil-Gas-Analysis Methods

Ever since the day that the science of applied geophysics was first started, there has been a continual development of methods, and a continual search for new principles upon which to base investigations. One of these newer methods that has been under development for some time, in other countries perhaps more than in the United States, is the method involving the analysis of soil gas.

In the process of soil-gas analysis, there are several different methods of operation, some of which are based upon the presence of petroleum derivatives in the actual free gas withdrawn from the surface soil by means of vacuum pumps. Others make use of a study of the adsorbed gas in the soil at some small distance below the surface of the ground. Others are based upon the analysis for wax in the surface soil.

The basis of the claims of these methods is the theory that wherever there is a deposit of oil there is a seepage of hydrocarbon vapors upward through the various strata to the surface. There will be a certain minimum density of heavier hydrocarbons at all points, but the presence of more than usual amounts will be indicative of the deposit. Of course, where there is a weakening of the strata above the deposit, however slight, perhaps due to the intrusion of a salt plug or a fault, the seepage through these zones of weakness will be greater, and the larger amount of adsorbed hydrocarbons in the top layers of soil will indicate the fact.

Electrical Methods

The presence of oil in any deposit depends upon several factors, of which the two main ones are the presence of oil producing materials, and the proper structure or trap to catch and store the oil. Most geophysical methods can serve only to detect structure, which they do in different ways. Since all materials conduct electricity to a greater or less degree, these structures are susceptible to measurement by electrical methods. In order to find regions or deposits of good electrical conductivity, it is necessary to introduce currents artificially into the ground and trace their behavior. From the knowledge thus acquired, as to how the current distributes itself under the various arrangements by which it is introduced into the ground, the effects of local regions of good conductivity are noted and the presence of certain formations revealed.

There are several different methods of measuring the earth's resistivity, all of which are more or less similar in principle. They involve the introduction of current into the ground through two or more electrodes, and the measurement of the potential at two or more other electrodes. Their differences lie in the relative positions of the various electrodes, or the manner in which the voltages are applied, the type of current used, or the type of indicating meter.

The simplest and best known electrode arrangement is the Wenner configuration, which makes use of four electrodes, two current, and two potential. They are spread in a straight line, generally with equal intermediate spacing, with the two potential electrodes in the center. Applying a voltage to the two outer electrodes causes the current to spread throughout the whole volume of earth between these electrodes. By measuring the current and the potential, a value of resistivity can be computed which is the average resistivity of the region between the electrodes.

Many of the common operating difficulties in earth-resistivity measurement, such as polarization, leakage currents, and earth currents, can be eliminated by the simple expedient of reversing the current from the battery. The Gish-Rooney method is similar to the Wenner method, except that it provides switching, by means of a commutator, to reverse both the current leads, and the potential leads. In each reversal the potential leads are connected after, and broken before, the current leads. This cycle is repeated about 30 times per second. The apparatus is illustrated in figure 5.

A variation of the four-electrode Wenner configuration is the Lee partitioning spread, in which a fifth potential electrode is placed in the exact center of the configuration. In addition to providing resistivity measurements as before, this arrangement provides the additional information re-

garding dissymmetry in the subsurface region under each half of the spread. This method is useful for the case where there is a dip of the beds, or where there are outcroppings or faults. For instance, if a fault line is crossed by the spread, and does not occur at the center of the spread, the side in which it does occur will show an average resistivity higher or lower than the other side, depending on the type of fault, and the nature of the fault zone.

Theoretically, the current that flows between the two electrodes fills entirely the underground space to an infinite extent. However, practically, the main part of the current flows in a region rather close to the surface, and the average resistivity measured corresponds to that at a depth of about one-third to one-fourth of the total current spread. This indicates that it is possible to change the depth of penetration of the current by merely altering the electrode spacing. This procedure of taking resistivity measurements by the Wenner method, with constantly increasing spacings is depth profiling. By this means, measurements to depths of several thousand feet are possible.

There are in general two methods of profiling by resistivity measurements. One is the depth profile just indicated, in which the electrode spacing is altered. The other is the constant-depth profile in which the electrode configuration is kept the same, but the entire spread is moved along the line of profile.

A recently devised variation of the steady-state measurements of resistivity is the electrical-transient method of prospecting. This involves electrode arrangements similar, in some respects, to those just described. Because of the large inductive effects between current and potential lines, the same linear arrangement of electrodes is used, but the potential electrodes are moved outside the space of the current electrodes.

By suddenly impressing a voltage between the current electrodes, a current builds up in the circuit in an approximately exponential manner depending upon the inductance and resistance in the circuit. At the same time a potential builds up between the potential electrodes, which more or less follows the shape of the current curve, but with much greater time constant. The exact form of the potential curve is not a true exponential, and it is the variation in this curve that is claimed to be indicative of the properties of the structure.

Geophysical Instrument Company

Figure 5. Gish-Rooney earth resistivity apparatus: left, measuring instrument assembly; right, commutator unit

In general this curve can be matched rather well by comparing it with the sum of two exponential curves of different amplitudes and time constants, and measurements are made on that basis. If a curve is plotted, with abscissas as distance along the line of profile, and ordinates some function of these amplitudes and time constants, then certain characteristic shapes of this curve are found, by trial, to be correlatable with the presence of faults, or other geoelectric anomalies.

Measurements are made in one of several ways. One is to take a picture of the transient by means of an oscilloscope and high-speed camera, and analyze the curve for its time constants. Another is to balance out the measured transient by another one artificially set up, and variable by means of changing resistances or capacitances. From the electrical constants of the dummy circuit, the time constant of the curve can be computed.

Well-Logging Methods

One important use of the electrical methods is in the electrical survey of wells. This was originally used as an addition to the driller's log and core log, for correlation purposes. However, by means of electrical measurements, additional information as to the porosity of sands and the presence of oil or salt water are indicated. Because of its value in the delineation of the boundaries of the various strata through which the bore hole passes, this method is extremely valuable in correlation work, and is, therefore, a useful tool for the geophysicist.

Electric coring is really an adaption of the circuits used for surface resistivity work, to measurement of the region surrounding the bore hole. One common circuit is the single probe configuration, in which two potential electrodes are maintained in fixed relation to, and above, one of the current electrodes, and the group of three raised and lowered together in the well. The second current electrode is at the surface of the ground.

By continuously recording the resistivity measured between the two potential electrodes, as a function of depth, a log of the well is obtained. With close spacing of electrodes, the penetration of the current is small, and the record represents the resistivity near the hole. With greater spacing, the penetration from the axis of the well is greater.

Alternating currents or commutated direct currents may be supplied to the current electrodes, and the corresponding potential measured at the probe electrodes. In addition to this derived potential, there is measured a spontaneous d-c potential which is generated in the drill hole. This may be due to the filtration of the mud filling the hole, into the formations, or to the contrast of the water filling the hole, to the fluid contained in the formation. The potentials measured are most intense opposite the permeable layers, so that the porosity log shows peaks opposite the sands, and flat curves opposite the impervious beds.

In practice, both the impressed and self-potentials are measured at the same time at the same electrodes, and a complete record of resistivity and porosity can be had in a single traverse of the well.

Thermal Logging

It has been found possible by means of a resistance thermometer, to take continuous measurements of temperature down a well. This record will provide further indication of the porosity of the beds, particularly when gas or liquid is issuing from any stratum. In the case of gas, the basis of this indication is that the expansion of the gas as it leaves the pores of the stratum and enters the well cools the surrounding space, and the difference in temperature is sufficient to be measured. The inflow of liquids from a porous stratum causes a change in the normal temperature gradient in the well, and thus the point of entrance can be detected. This method is also used for detecting points of water entrance into cased wells.

Gamma-Ray Logging

Because of the difficulty of applying the electrical logging methods in cased wells, it is necessary to look to other effects that are measurable. One such method that has been proposed involves the measurement of the radioactivity down the well. By using a modified Geiger counter circuit, and measuring the frequency at which the circuit is tripped by the radiation, a log of the gamma-ray emanations from each stratum is had.

This log appears to correlate very closely with the electrical-porosity log (obtained before casing is set), indicating that porous sands show a minimum of radiation, and can be recognized by this effect. While not yet proved by actual use, this method shows considerable promise.

Seismic Method

Modern methods of petroleum production and oil-field development require a maximum of subsurface information in advance of drilling. In the search for new oil deposits, the more obvious structures have already been discovered and tested. New ones must be found by methods capable of interpreting the more complex subsurface conditions where surface geology affords little information. In many cases these structures will be deep seated, and will have little or no surface expression. Once found, structures must be tested by the drill before their potentialities as oil producers may be known, and since such drilling is costly, it is highly important that such subsurface information be as complete as possible from surface studies before any drilling is done. To this end, operators are utilizing the most advanced instruments in their search for oil. The most useful instrument, and at the present time, the most accurate one, is the reflection seismograph.

A seismograph is an instrument for recording the shock of earthquakes. In applied geophysics, the seismograph is an instrument for recording vibrations from the explosion of a small charge of dynamite buried in the ground. The responses of the seismographs are recorded photographically on records called seismograms. From the data on these seismograms, the time of travel of the seismic or elastic wave through the various rock strata can be determined, and much can be learned of the character and

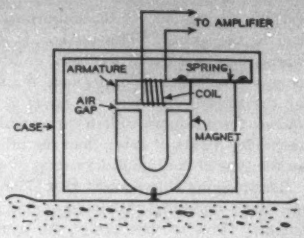


Figure 6. Schematic diagram of a reluctance-type seismometer

structure of these subsurface beds, as well as the depth of the structure itself.

The earliest type of seismic equipment was the refraction seismograph, which provided an accurate measure of the velocity of seismic waves in the ground. Its value in the location of salt domes was great, because the materials of which the domes were composed had abnormally high elastic moduli. Large charges of dynamite were fired, and the arrival of the shock recorded on a number of seismographs set more or less fan shaped around the shot point. The times of arrival of the first waves were recorded and measured. This time, and the distance, usually of the order of several miles, gave a measure of the average velocity of the waves in the ground. If the line joining the shot point with any recorder coincided with the position of a salt dome, this time of travel would be abnormally short, and so would indicate a section of the earth in which the velocity of seismic waves was high.

As the number of undiscovered salt domes became less and less, and the number of new discoveries became fewer, the refraction seismograph became of less value. Because of the great attenuation of the waves refracted from great depth, enormous charges of dynamite had to be used in order to have a detectable received wave, which made operation expensive. However, it was not the cost of the method so much that caused its disfavor as it was the discovery that the *reflected* seismic waves from the explosion could be used to better advantage than the *refracted* waves.

In the reflection seismograph, the detectors, or seismometers, are vertical-component vibration detectors, and are sensitive to the waves that travel downward from the explosion and are reflected back from the surfaces of discontinuity between the subsurface strata. Knowing the time of travel of such a wave, and the average velocity over the path, the depth of the reflecting layer can be easily determined. It has been found that reflected waves will be returned to the surface from every plane or layer that represents a sharp difference in the elastic properties or density of the rocks above and below that particular plane or subsurface layer.

Reflection seismograph equipment is made up of seismometers, amplifiers, recorders, and miscellaneous equipment. The seismometers are used to pick up the seismic vibrations and convert them into electric currents, which are applied to amplifiers, and thence to a multitrace recorder. Individual seismometers, or groups in series, are applied to each channel of amplifier and recorder. While

theoretically it would be possible to make a depth determination by the use of only one seismometer, and one channel of amplifier, practically this is never done. One reason is that there are other types of waves that reach the seismometer before the reflected wave, and identification of the latter is difficult. Furthermore, by the use of two or more detectors, it is possible to determine not only the depth of the reflecting plane, but also its inclination.

Early seismic work failed to recognize this advantage. At that time the value of the additional detectors was mainly to be able to recognize the reflection. The seismometers being at different distances from the shot point, the direct waves would arrive at different times. But since the depth of the reflecting plane is large compared with the separation of the seismometers, the length of path for the reflected waves is almost equal, and they arrive at each seismometer simultaneously. This feature was evidence of the reflection. The interpretation of the operation of the seismograph in this way was the result of the first use of this instrument in locations where the dip was slight, and consequently the only quantity of interest was the depth. This use of the reflection seismograph was for the purpose of correlation. By determining the depth of a given bed (from which the reflection was recognized) at a number of points in a given territory, the contour of the surface can be plotted. This is still the main type of information derived from 50 to 75 per cent of the reflection-seismograph operations.

When the seismograph was used in locations of high-dipping beds, the fact that the reflections did not arrive at each seismometer at the same instant was evident, and its interpretation in terms of the dip of the reflecting plane discovered. This opened a whole new field of application, and today this instrument has considerable application in dip work.

The information read from the seismogram is the time of travel from the instant of shooting to the arrival of the reflected wave, and the "move out time," which is the difference in time of arrival of the reflection at the seismometers most widely separated. This information, with the horizontal spacing of the seismometers, serves to provide the value of depth and dip of the reflecting planes. When these are plotted, they provide a profile of the reflecting surfaces.

Theoretically, the maximum number of seismometers needed is the number that will provide an interval along the surface small enough so that the time of arrival of the reflected waves at adjacent seismometers will be within a few thousandths of a second. However, there are other advantages of additional seismometers, and the present trend is toward the use of more and more of them. From the point of view of signal-to-noise ratio, the more seismometers that are added in series, the less the relative amplitude of background or random vibrations. Furthermore, by proper placement of seismometers in series groups, they may be spaced so that the voltages induced as a result of the direct, or ground, wave will be out of phase in each one, and the sum of their output voltages will be zero. Practically this result is never quite reached, although there is an immense practical benefit in the reduction of random vibrations. For random waves, the improvement is proportional to the square root of the number of seismometers.

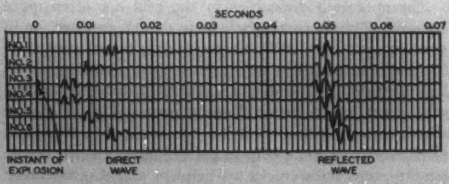


Figure 7. Idealized seismogram showing direct and reflected waves

Another feature that is often used to aid in correlating across the record is the use of groups of seismometers recording on two traces. This overlapping of seismometers tends to include portions of the energy on one trace in the energy of the adjacent traces. This makes it easier to recognize the reflection on all traces, and to correlate between the two seismometers that are to serve for the determination of move-out time.

Before the records can be interpreted, that is, before the depth and dip can be computed, the average velocity of travel for the reflected waves must be known. A general variation of velocity with depth can be postulated upon the increased density and elasticity of the deeper sediments. However, in each case, it is necessary actually to measure the velocity of the seismic waves. This is done by the use of a special type of seismometer, which is lowered into a well, and the travel time measured for waves initiated by a dynamite charge near the collar of the well. By measuring the time of travel of these waves for different depths of the seismometer, the curve of average velocity can be plotted as a function of depth.

Seismometers are vibration detectors, or electromechanical transducers. Most commonly used are the reluctance and dynamic types. However, seismometers utilizing carbon-microphone-button, piezoelectric, and magnetostrictive elements have been built and used. The greatest sensitivity and ruggedness are associated with the magnetic types. The construction, illustrated in figure 6, involves a spring-mounted mass of a certain period of oscillation which will best record the vibrations to be detected. The value of damping is generally quite critical, and various methods of obtaining the damping are used. Some are oil damped, others electromagnetically damped, and some even air damped. These units are extremely sensitive, and will record minute vibrations, of the order of ten 1,000,000ths of an inch in amplitude.

The amplifiers used are resistance-capacitance coupled, or transformer coupled. They are generally most sensitive in the range of from 30 to 100 cycles, and various systems of frequency discrimination are used. This is a matter of individual choice with the operators or observers. In some instances amplifiers are provided with several discriminations which are available at the turn of a switch, or by the change of a small filter unit.

Camera problems are similar to those in conventional

Figure 8 (left). Marsh-type drill

Figure 9. Recording truck operating in wooded area

oscillographs except that here the frequencies to be recorded are generally lower, and elements of greater sensitivity can be provided.

Timing problems are quite critical. It is necessary to be able to read time to 1/1,000 second, and consequently is necessary to have a very accurate time source. There are several systems for timing records. One involves the use of a temperature-corrected tuning fork driving microphone buttons to provide a 100-cycle source of voltage. This drives a small synchronous motor with a time wheel that periodically interrupts the light from the exciting lamp, thus providing a line shadow across the record. Another system makes use of a tuned reed that is set into vibration at the instant of firing of the charge, and which interrupts the light beam periodically. Another system makes use of a vacuum-tube-driven fork and timing motor. In each system, the records are marked by time lines across the sheet, each 1/100 second apart. The records are then estimated to 1/10 division, or to 1,000ths of a second. Reading time to 1/1,000 second provides depth information to the order of about five feet. (See figure 7.)

The exact time of explosion must be determined very accurately so that the travel time can be measured. One method is to wrap the dynamite with a small copper wire through which a current is passed. This current is cut off by the breaking of the wire at the instant of the explosion, and the record shows this time. Another method involves recording the instant at which a small metal fuse ruptures in the cap that detonates the dynamite. In this case the current from a blaster is passed through the fuse, and its heating detonates the charge. The rupture of the circuit takes place as a result of the detonation.

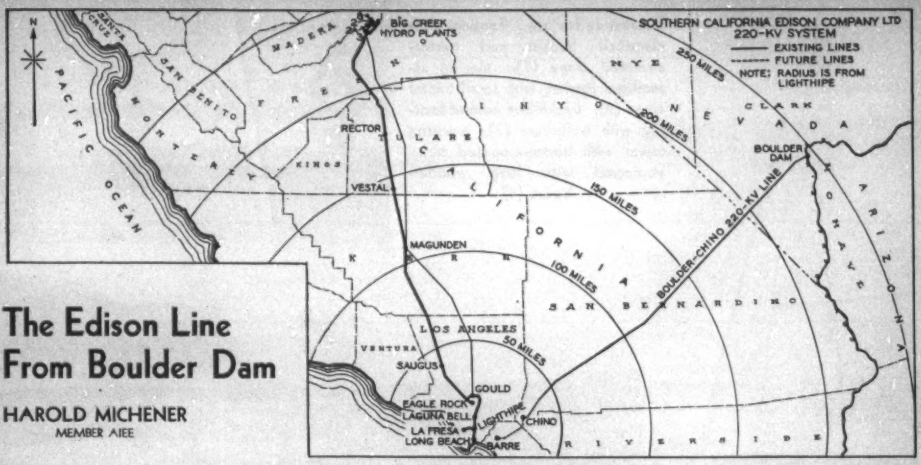
In addition to these major problems, there are the problems of photography involved in the developing of the records, telephone or radio communication to and from the shot point, and the construction, care, and handling of cables. This is quite important, particularly for some of the longer spreads.

The most important part of the recording of reflections is the matter of volume control. Since the seismometers are in general quite close to the shot point, the incident energy immediately after the first arrivals is enormously greater than that after some time has elapsed. In other words, in order to hold the record to uniform amplitude, it is necessary to provide some sort of control in which the beginning of the record can be attenuated in a ratio of some 2,000 to 1. Early equipment made use of fixed steps of attenuation. Since it was obviously impossible to choose the exact instant when the switch should be thrown from one step to the next, only small portions of the records were of proper amplitude, and so shots had to be repeated in order to be able to get all portions of the record at proper amplitude.

Later equipment made use of fixed-rate gain controls, in which the attenuation started at a very high value and was gradually reduced with time according to a fixed exponential rate set by the discharge of a condenser. By choosing the proper rate, a record of more or less uniform amplitude could be obtained. Later methods involve the use of automatic volume control of the radio type to provide a record of constant amplitude throughout its length. The matter of proper volume control is extremely important as the number of strings increases, in order to avoid having strings tangle (in the case of the string camera) and in order to make the record more readable.

The actual instruments used for the recording of the travel-time data are only a small part of the entire seismic equipment. The full equipment consists of a rotary drill used for drilling the shot holes, which may vary from very shallow holes to holes up to some 500 feet in depth, a water truck which carries drill pipe and water for drilling, a shooting truck which carries the dynamite and water to tamp the charge, and the recording truck. In addition, there is equipment for the permit man and surveyors. The drilling and recording operations are illustrated in figures 8 and 9.

The operating difficulties in the field are often quite serious. This is particularly true in wet weather, or in swampy territory. All these truck equipments are heavy, in spite of attempts to reduce the weight of all items. In bad territory, oversize tires are commonly used, which permits operating in even the worst weather. In any case winches are provided so that when trucks become mired they may have some help in getting out. In real marsh country even these trucks are helpless, and it is necessary to go to an entirely different type of vehicle in which the wheels are huge air drums able to float the truck in water.



The Edison Line From Boulder Dam

HAROLD MICHENER
MEMBER AIEE

To transmit its allotment of power from Boulder Dam to its system, the Southern California Edison Company, Ltd., has completed and recently placed in operation a 233-mile, single-circuit, 220-kv line of simple and time-tested design, the principal features of which are here outlined.

SHORTLY after the passage of the Federal Water Power Act in 1920, the Southern California Edison Company, Ltd., began a study of the possibilities of power development on the Colorado River. Topographic surveys were made, in collaboration with the United States Geological Survey; a river-gauging station installed at Lee's Ferry, Ariz.; and core drillings made at the Glen Canyon and Callville dam sites. Having completed a comprehensive plan for power development between Glen Canyon and Topock, the company filed application for license with the Federal Power Commission. The application was pending when Congress passed the Boulder Canyon Project Act, December 21, 1928, and subsequently was refused.

According to the terms of the Act, the power was allotted by contract before construction of Boulder Dam was begun, to several distributing agencies including the Edison company. Co-operating with the United States Bureau of Reclamation and other agencies on plans for the equipment of the powerhouse, the company arranged that a unit system—one generating unit to a bank of transformers—should be provided for the four 82,500-kw units tentatively allotted to its use. This plan eliminated the low-voltage generator switches for these units, and the Arizona side of the powerhouse was designed and built accordingly.

Study of transmission facilities indicated that a single-circuit 220-kv line, similar in construction to those long in operation on the Edison system and capable of delivering 150,000 kw, would be most economical for the delivery of power from the first two generating units to be installed for the company. Construction of two lines with cross-over switching stations was considered unnecessary, since the powerhouse is but one of three major sources of the company's power.

Chino substation, an existing 66-kv and 11-kv substation, at Chino, San Bernardino County, Calif., and Barre substation, now under construction near Stanton, Orange County, Calif., were chosen as receiving stations for the first line. Each has a 75,000-kva 220/66-kv transformer bank and a 50,000-kva synchronous condenser. Construction of the line originally was planned for completion by the summer of 1938, since the power would have been required if dry weather had affected the company's major water power plants on the upper San Joaquin River. However, since an unusual abundance of water was available in that drainage area in the spring of 1938, construction of the line was retarded. The first Edi-

Transposition on a dead-end tower; the only type of transposition used on the line

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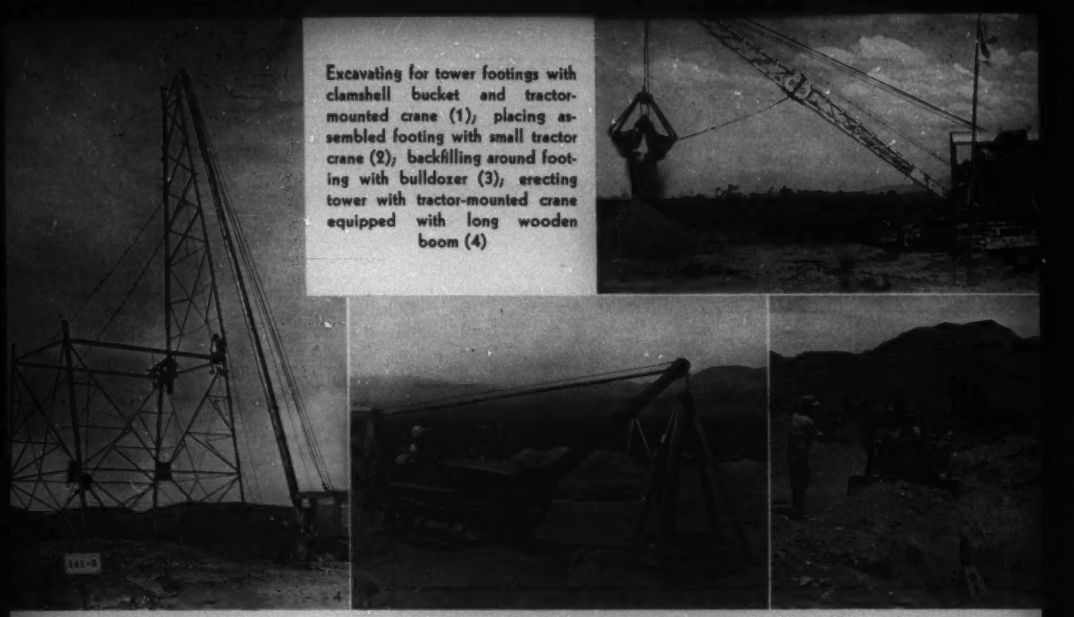

Excavating for tower footings with clamshell bucket and tractor-mounted crane (1), placing assembled footing with small tractor crane (2), backfilling around footing with bulldozer (3), erecting tower with tractor-mounted crane equipped with long wooden boom (4)

son company unit at Boulder Dam began delivering power over the line in July 1939, according to the revised schedule.

Protection for the Line

Since most of the short circuits experienced by this company on its 220-kv lines during 15 years of operation have occurred between one conductor and ground, and since this line would be isolated from other 220-kv lines, it was decided to install ground-fault neutralizers (Petersen coils) in connection with the banks of transformers on both ends of the line.

In addition to the ground-fault neutralizers, which are expected to prevent interruptions to service on this line whenever one conductor becomes temporarily grounded, the line is protected by four-element instantaneous overcurrent relays, one element being used for residual currents when phase-to-ground faults occur at times when ground-current neutralizers are short-circuited, in which cases the circuit breakers at each end of the line open simultaneously for faults near the center of the line, and in sequence for faults near the ends of the line. The other three elements of each are used for phase currents to open the line at one end in cases of phase-to-phase faults near that end of the line. To open the other end of the line in such cases, and to clear the line when a phase-to-phase fault occurs near the center of the line, it is necessary to use at each end of the line three double-element balanced-current relays. These are adjusted so that if the phase current in one element is ten per cent greater than that in the other element, the tripping contacts will close.

No sectionalizing switches have been installed in this line, it being planned that means will be provided for determining the location of a permanent ground fault on a conductor without sectionalizing the line.

Description of Boulder-Chino Line

The route of this 233.3-mile line is closely defined by Boulder City, the stations of Nipton, Cima, and Sands on the Union Pacific Railroad, Pisgah on the Santa Fé Railroad, Lucerne Valley, Cajon on the Santa Fé Railroad, and the city of Chino. This route was chosen, after careful investigation of other possible routes, on the basis of lesser estimated cost, avoidance of bad ice-loading conditions in the San Bernardino Mountains, avoidance of interference with communication lines, and as great a distance as feasible from other transmission lines delivering power from Boulder to the southern California area. Certain disadvantages were recognized as inherent in some sections of this route, such as the difficulty of making and maintaining a road through the blow-sand of the Devil's Playground, in the vicinity of Sands, and the footing difficulty in the Lucerne dry lake. However, this route seemed to have a lesser aggregate of evils than any one of the other routes considered.

The region traversed by the route selected is mostly arid desert land from Boulder to the southern edge of the San Bernardino Mountains, a distance of 212 miles. In this section, about 65 per cent of the lands crossed are owned by the Government, either Federal or State; land values are low and the necessary ties to existing surveys few; temperature ranges are great, from 0 to 135 degrees Fahrenheit; high winds, which fill the air with sand, are

Type of Construction, Boulder-Chino 220-Kv Transmission Line

Spans.....Minimum, 288 feet; maximum, 3,128 feet; average, 1,398 feet.

Towers

Type.....Wedge type so commonly used for high-voltage single-circuit transmission lines.

Number.....Total 880, or an average of 3.77 per mile; 67 anchor, 813 suspension.

Height to Crossarm.....Seventy-foot anchor, 78-foot suspension, with standard legs; or provided with 3 feet shorter, 6 feet shorter, 3 feet longer, 6 feet longer legs; or with extensions 6, 12, 18, or 24 feet in height.

Weights Without Footings..Type *L*, 9,171 pounds; type *H*, 10,960 pounds; type *S*, 13,788 pounds; type *D*, 14,994 pounds.

Footings.....Normally pyramid-type steel footings. Plates or stanchions added where greater bearing area required due to sand. Concrete footings in and near dry lakes, both where bearing value of soil is poor and where corrosivity of soil is great.

Conductors.....Steel-reinforced aluminum cables, 605,000 circular mill, 0.994-inch diameter, 30/19 strand. Horizontal configuration, 23 feet separation. Ultimate strength 30,000 pounds. Maximum design tensions 14,000 and 10,000 pounds, under heavy and light loading conditions respectively.

Overhead Ground Wires...Two one-half-inch, seven-strand, zinc-coated, extra-high-strength steel, located approximately midway between and 12 feet above the conductors at the towers. Ultimate strength 26,900 pounds. Maximum design tensions 11,000 and 8,400 pounds under heavy and light loading conditions respectively.

Counterpoises.....Two radial counterpoises per tower where footing resistance was near or greater than 100 ohms. Each counterpoise consisted of four one-half-inch, seven-strand, galvanized-steel cables, 200 feet long, buried from 1½ to 2 feet deep in the same trench. Average tower footing resistance after installation of counterpoises, 9.3 ohms for the 54 towers where counterpoises were installed.

Insulators.....Ten-inch diameter, 5¾-inch spacing, heavy section, cap and pin, ball-and-socket connection, suspension insulators. 15 units in suspension strings and two strings of 16 units each in dead ends. 25,000-pound units in dead ends and peak suspension positions in heavy loading districts; otherwise 15,000-pound units in both dead-end and suspension assemblies.

Hardware.....Mostly forged steel of standard commercial lines with modifications to fit requirements. Arcing horns at suspension clamps and at both dead-end yokes, but no insulator grading ring. Aluminum Company of America design of conductor splices and compression dead ends. Nicopress steel splicing sleeves for ground wires. Bolted cast-steel clamps for ground-wire dead ends. Bolted cast-iron clamps for attaching ground wires rigidly to suspension towers, except where line angle is greater than three degrees, in which cases ground wires dead-ended. Stockbridge vibration dampers on both the conductors and ground wires.

Bird Guards.....Saw tooth on outer six feet of crossarms; pans on center eight feet, with pan extensions on inner end at angle towers.

Communication.....Two-wire telephone line roughly paralleling the transmission line, and most of the way in combination with existing communication circuits. Also, carrier-current telephone on transmission line.

frequent; existing accommodations for construction crews are few and far between, and suitable locations for camps away from these existing accommodations are nonexistent. For these reasons, methods of survey and construction were used which would require a minimum number of men to complete the line within the desired time limit. The stadia method of survey and the use of adequate power equipment for road building and line construction were the principal means to this end. The illustrations on page 464 show some of the equipment used, and completed towers are shown on this page and page 463.

Completed suspension tower (type H)

The construction work was begun in November 1936 and carried on by the Southern California Edison Company, Ltd., until June 1, 1937, during which time a large portion of the road was built and a small portion of the footings was set. On June 1, 1937, Stone and Webster Engineering Corporation took over the construction of the line. The survey work, the acquisition of right of way, and the office engineering remained in the hands of the Edison organization. The type of construction used for the line is indicated in the tabulation.

The operating record of the Boulder-Chino line will be watched with interest, chiefly because of the use of ground-fault neutralizers and because of the high load imposed upon the line.

Lightning Strokes in Field and Laboratory

P. L. BELLASCHI
MEMBER AIEE

Recent developments in the lightning-stroke generator have made substantial contributions to lightning research

SINCE the time that currents of lightning-stroke intensity were produced in the laboratory,[1] lightning generators have been the object of continual development and of extensive application.[2,3] This article refers briefly to the developments of the lightning-stroke generator in recent years and also to substantial contributions to lightning research that the new forms of generator have made possible.

The arrangement in figure 1 consisting of the high-voltage generator (A), the high-current generator (B), and

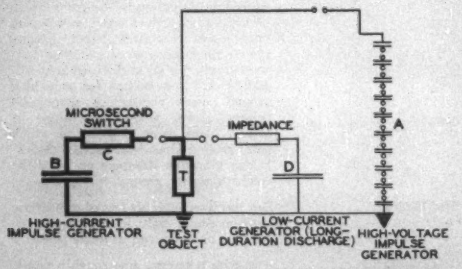

Figure 1. Schematic diagram of lightning-stroke generator

the microsecond switch (C) has been used for several years. For engineering purposes and research where the voltage and the high current of the stroke (figure 2) are the two elements of importance, this arrangement of the lightning-stroke generator is the one to use.

Visual observations of lightning have indicated the occurrence of prolonged discharges estimated to be in the order of a fraction of a second or more. The presence in lightning strokes of long-duration low-current components following the initial high-current discharge has been well established photographically by B. F. J. Schonland and his associates. The phenomena of the stroke discharge that give rise to the sustained components have been analyzed in considerable detail by them.[4] Fulgurites,[5] heavy fusion of metal objects, fires, and similar effects have likewise established the presence of sustained low-current components in lightning strokes.

One form of the lightning-stroke generator that has been devised to produce the combined voltage and current components (figure 2) of the lightning stroke is shown schematically in figure 1. Considerable laboratory research with this and similar arrangements and correlation of extensive test results on long-duration components with corresponding field data and records have established that:

"The effective current of long-duration components of lightning strokes may range from a few hundred to several thousand amperes. The corresponding durations apparently range from 0.1 second, and even longer in some cases, to about 0.001 second."

It is of interest to note that the high-current components and the long-duration components of low current in lightning strokes have recently been recorded by the oscillograph in field investigations in Europe[6] and in the United States.[7]

Some of the results from tests conducted with various forms of the lightning-stroke generator are summarized in tables I and II. From these and from other findings it is clearly apparent that shattering, bursting, explosive effects, and similar damage to objects hit by lightning are caused largely by the high-current short-duration discharge of the stroke,[8] whereas, fires, heavy fusion of metal, fulgurites, extensive burning, and other similar effects result largely from the relatively low-current components in the stroke discharge that may be sustained even for a substantial fraction of a second.

Figure 3 shows a stack of excelsior which was ignited instantly on discharging through it a long-duration current from the lightning-stroke generator (see table I for current duration). The fulgurites in figure 4 were produced by similar long-duration discharges through sand. These were observed very shortly after the sand was fused

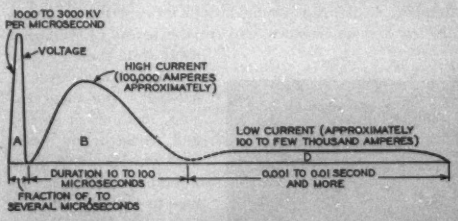
1000 TO 3000 KV PER MICROSECOND
VOLTAGE
HIGH CURRENT (100,000 AMPERES APPROXIMATELY)
A
B
LOW CURRENT (APPROXIMATELY 100 TO FEW THOUSAND AMPERES)
D
DURATION 10 TO 100 MICROSECONDS
FRACTION OF 1 TO SEVERAL MICROSECONDS
0.001 TO 0.01 SECOND AND MORE

Figure 2. Schematic representation of lightning-stroke discharge

and to all appearances the fulgurites formed constituted a glowing, intensely white-hot mass.

The relative loudness of the discharge for high currents of short duration and for low currents of long duration

P. L. BELLASCHI is section engineer, transformer engineering department, Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Table I. Resultant Condition of Various Test Specimens When Subjected to Measured Current Discharges of Long and Short Duration

Test Specimen	Surge Current* Crest Value (Amperes)	Surge Current* Total Duration (Second)	Effects
Discharge through fine carborundum	4,700	0.028	Fulgurites produced. External diameter approximately 8 millimeters; internal diameter approximately 3 millimeters.
Discharge through sand contained in fiber tube	17,000	0.0045	Fulgurites produced. External diameter approximately 13 millimeters. The fulgurites were observed at the instant produced. They were then of white incandescence (fused sand) and externally they appeared in a substantially solid state.
Discharge through sand	100,000	0.0004	Sand scattered by blast action of discharge. Test repeated with similar results.
Discharge through clean cotton cloth	4,700	0.028	Cloth ignited. Test repeated with similar results.
	17,000	0.0045	Cloth ignited. Test repeated with similar results.
	100,000	0.0004	Cloth scorched and torn but *not* ignited. Three holes 15 to 30 centimeters torn in cloth. Specimen blown off by blast action of discharge. Test repeated with similar results.
Discharge through excelsior	4,700	0.028	Excelsior instantly ignited.
	100,000	0.0004	Excelsior scattered through laboratory but *not* ignited.
	100,000	0.0004	Excelsior more loosely packed than in the preceding test. Excelsior somewhat scattered; the part left on test stand ignited and gradually set into flames.
Discharge through paper (white paper used in drafting)	2,000	0.0023	Paper ignited.
Discharge through paper (white, brown express, etc.), through cloth, etc.	100,000	0.0004	Numerous tests made on paper, cloth, etc. In no instance was material ignited. Some scorching was the only effect observed.
Lightning-stroke test of distribution wood poles. Approximately 60 poles tested. Occasionally tests were repeated after shattering and splintering the pole. Some of the poles were dry, others wet	50,000	0.0001	Of approximately 60 poles tested, in only one instance was the wood of the pole ignited. In this particular case the pole had already been tested two or three times and was well splintered and broken. Moreover, the wood of this pole was well dried.

* Surge current recorded with the cathode-ray oscillograph.

Table II. Relative Loudness of Measured Current Discharges of Long and Short Duration in Air

Surge Current Crest Value (Amperes)	Surge Current Total Duration* (Second)	Relative Loudness of Noise
100,000	0.0094	Unbearably loud; painful to ear.
17,000	0.0045	Painful effect substantially reduced.
4,700	0.028	Noise fully bearable and similar to removal of cork from bottle.
2,000	0.0023	Noise inaudible unless person stood in laboratory.
850	0.0023	

* Duration to crest (front) is proportionately greater for the respective discharges from the top to bottom of the tabulation.

Figure 3. Excelsior ignited instantly when a long - duration current from the lightning - stroke generator was discharged through it

are compared in table II. As previously established, the thunder following the lightning flash results from the explosive expansion of the channel and is due to the high-current initial discharge. Strokes to or from elevated objects, between clouds, and under special conditions have been observed in which the current is largely a long-duration component.[7,9] Such discharges naturally are not accompanied by appreciable noise.

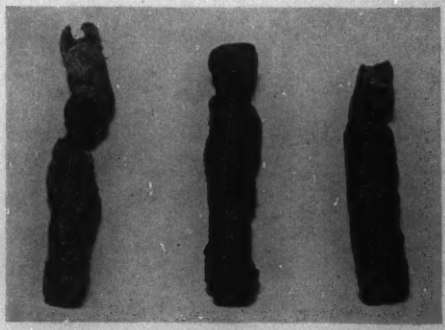

Figure 4. Fulgurites produced by passing long-duration discharges from the lightning generator through sand

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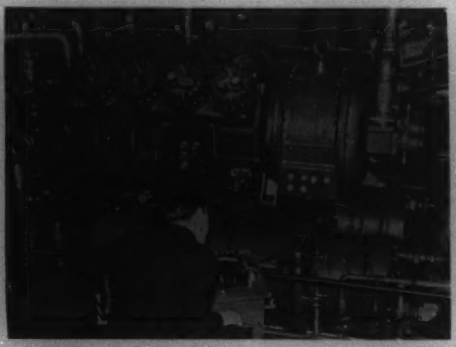
Refrigerant-Cooled Motor Drives 100-Ton Compressor

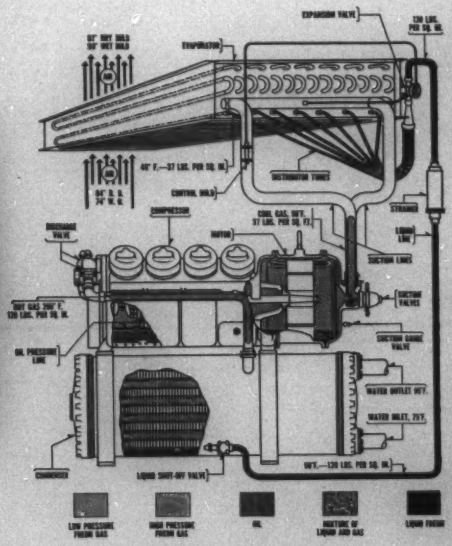
COMPLETION of a hermetically sealed 100-ton 16-cylinder air-conditioning compressor unit driven by a 100-horsepower 1,150-rpm refrigerant-cooled motor recently was announced by the air-conditioning department of the Westinghouse Electric and Manufacturing Company, East Springfield, Mass. The new unit is intended particularly for stores, factories, theaters, and similar applications. Of extremely compact design the unit is said to require only one-third the space that would be required by a compressor of conventional design for the same capacity, and to weigh only two-thirds as much.



Compressor unit undergoing test

It weighs 4,200 pounds and its over-all dimensions are: length 90 inches, width 34 inches, and height 36 inches. The single-unit type of construction permits of sealed-in lubrication, and a reversible oil pump prevents harm when motor phase connections are inadvertently reversed, thereby reversing the direction of rotation. The refrigerant is Freon.

A typical operating cycle for the new compressor unit is shown in the accompanying diagram, as well as the general design of the unit itself. From the suction manifold of the evaporator the relatively cold refrigerant gas sweeps through the windings of the driving motor. After cooling the motor, the low-pressure gas enters a manifold, then through the intake feather valves, into the cylinder where it is compressed and expelled through separate feather-valve ports into the high-pressure discharge line. The high-pressure gas passes down into the condenser where it is condensed by contact with the water-cooled tubes. Liquid refrigerant enters the liquid line from the bottom of the condenser, passes through a strainer, and enters the expansion valve. The liquid begins to expand



Typical cycle of operation

into a gas as it passes through the expansion valve and distributor tubes, and continues to expand during its course through the evaporator. In this process, the air passing over the evaporator fins is cooled, as a portion of its heat is absorbed through the evaporator tubing walls by the boiling refrigerant inside. The refrigerant is completely vaporized by the time it reaches the valve control bulb, and enters the suction line as a low-pressure gas to complete the cycle. Temperatures and pressures shown are not exact but merely indicative of general conditions in a typical cycle.

Vertical-Shaft Generators—

Some Problems and Their Solutions

A review of some of the problems involved in the design and construction of vertical water-wheel generators, and methods of solution

H. R. SILLS
MEMBER AIEE

THE DESIGN of electrical apparatus "involves the correlation of three distinct kinds of engineering: electrical, mechanical, and thermal. In general, no one of these three aspects of design can be given first place in importance, although in particular cases the application and duty of the apparatus may determine one or another aspect as the limiting feature.

"In designing a new machine, an engineer has therefore to visualize not the physical appearance of the machine but rather its three interrelated circuits—the electrical, mechanical, and thermal. By shifting his point of view he can bring any one circuit into the foreground, just as in staring at a certain kind of optical illusion one sees first one figure, then another, although the actual lines in view remain unchanged. To design any one of these circuits is a comparatively simple matter; it is the coordination of the three circuits to best advantage which is the real engineering problem. Like in the optical illusion in which it is easy to see any one figure at a time, but extremely difficult to see all figures at the same time, it is correspondingly difficult in design to visualize all three circuits simultaneously. But difficult or not, the designer must keep all of them and their usually conflicting requirements in view continuously."*

This introduction, quoted from a paper by C. Concordia,* admirably defines the fundamental problem back of the design of vertical-shaft generators. It would be a fairly straightforward matter to talk of the electrical, mechanical, or thermal problems of generator design were each of these not influenced so greatly by limitations introduced by the other two. A quite satisfactory electrical design could be laid out that would be utterly impracticable because it might neither hold together nor dissipate the heat generated by its losses.

It must be borne in mind that a vertical-shaft generator is tailor-made equipment, designed to suit particular requirements in the same manner as a bridge is designed; and, like a bridge, it is first built on paper on the basis of fundamental theory and practical experience.

Energy in a Hydroelectric System

The first law of thermodynamics states that the energy in an isolated system remains constant and cannot be increased or diminished by any physical process whatever. The second law is that of the degradation of energy, according to which the result of any transformation of

Essential substance of a paper presented at a meeting of the AIEE Toronto Section, Toronto, Ontario, Canada, January 27, 1939.

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* Some Remarks on Design Engineering, C. Concordia, *General Electric Review* July 1936, page 317.

energy is a reduction in the quantity of energy available for useful work.

By considering all types of energy as a single concept, irrespective of whether it is hydraulic, mechanical, electrical, magnetic, or thermal, it is possible to sketch a flow chart of energy from the penstock of a hydroelectric plant to the transmission line as shown in figure 1. A diagram of this type gives a useful composite view of where the energy goes, the relative amount of the losses and the size of the reservoirs of potential energy. It may be seen that in the mechanical system sufficient potential energy is stored in the flywheel to supply or absorb full power flow for between two and five seconds. The whole of this potential energy cannot be used, as it would mean bringing the machine to a standstill; but for known load changes and governor response, it is possible to determine the frequency change. Likewise, in the excitation circuit there is a supply of potential magnetic energy that is drawn on to supply excitation for momentary or transient loads until the regulator can adjust the excitation to suit the load. In the thermal circuits, there are considerable reservoirs of sensible heat in the mass of copper and iron of rotor and stator that can absorb considerable momentary increases in losses without a proportionate increase in temperatures. These values can all be expressed in time, as the dimensional formula for power and heat flow is L^2MT^{-3} and for energy and heat L^2MT^{-2} (where L represents length, M mass, and T time); consequently the ratio is expressed in time.

This concept of total energy flow is the same for horizontal as for vertical machines. The design of the electric circuit is the same irrespective of whether the machine has a horizontal or vertical shaft. The fundamental difference between a horizontal-shaft generator and a vertical-shaft generator is that in the former gravity acts perpendicular to the shaft, and in the latter parallel to the shaft. Mechanically this is a large difference.

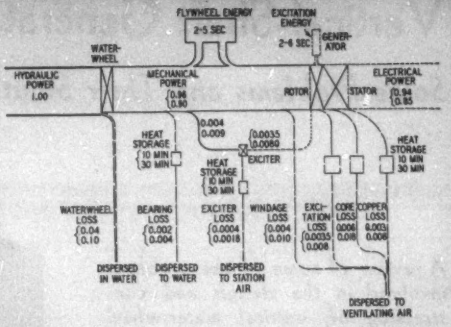


Figure 1. Flow chart of energy in a hydroelectric system

Weight and Its Support in a Vertical Generator

Vertical-shaft generators are massive pieces of equipment, and the forces due to gravity alone are large. The average generator of more than 5,000 kilovolt-ampere will weigh between 2,000 and 3,000 pounds per kilovolt-ampere per revolution per minute. Of this weight about 26 per cent is in the stator, 55 per cent in the rotor, 5 per cent in the base, and the other 14 per cent in the supporting brackets and miscellaneous parts.

The first thing the machine must do is support its own weight both when assembled and as individual parts during fabrication and shipping. Figure 2 shows these forces. Sketch *A* indicates the weight of the individual parts as a factor of the total weight; *B* shows the distribution of weight when the rotor is suspended from a thrust bearing on the upper bracket; *C* the distribution when the weight is supported on the lower bracket. In addition to the weight of its own parts, the shaft supports the weight of the water-wheel runner and shaft shown in *D* and the reaction of the thrust of the column of water turning the wheel as in *E*. The weight of water-wheel runner and shaft and the water thrust is from 50 to 70 per cent of the weight of the unit for a Francis-type wheel, and from 150 to 200 per cent for a propeller-type wheel. It is this proportionately large thrust load that is the outstanding feature of vertical-shaft generators, and probably the most important single point in determining the general mechanical construction.

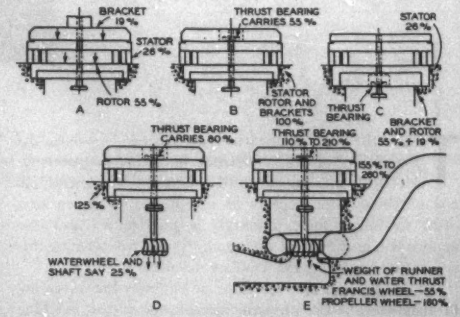


Figure 2. Distribution of weight in a vertical-shaft water-wheel generator

Several types of thrust bearings have been developed that are capable of carrying these large thrust loads (up to 3,000,000 pounds) reliably. Such bearings in the large sizes are of the spring-supported or pivoted-shoe type. In the smaller machines thrust bearings of the antifriction type sometimes are used. The bearing introduces no particular problem in itself, but the question of where it is to be placed, and how it is to be supported is a problem. Of the many aspects of this problem, some are inherent in the generator, but most of them are dependent upon requirements of the water wheel and the power-hourse design.

The water-wheel builders want a stiff bracket support

to be able to use small clearances in their wheels. It seems to be more or less agreed that a vertical deflection of $^1/_{32}$ inch from no load to full load is satisfactory for a Francis-type runner and $^1/_{16}$ inch for a propeller type. The water thrust (the only variable part of the thrust load) is about 33 per cent of the thrust-bearing load with a Francis wheel, and 66 per cent with a propeller-type wheel, so a total deflection at maximum load of approximately $^3/_{32}$ inch seems reasonable. From the point of view of the generator this amount of flexibility of the bracket is highly desirable, because excessive stiffness can only be secured by great depth in the bracket, which throws the proportions of the bracket out of line, increases the weight and cost, takes up valuable space, and makes the reaction on the bracket supports difficult to equalize, causing uneven distribution of the stresses.

In further explanation of the foregoing point, the thickness of the oil film that carries the load is about 0.001 inch and the thrust bearing may be from 80 to 100 inches in diameter; this requires that a level of 1 in 100,000 be maintained under all conditions of load in order to have equal distribution of the load over the bearing surface. No foundation will maintain such a precise level, and no bracket will not warp more than this amount from temperature changes. Obviously then, the alignment of the rotating and stationary parts of a thrust bearing must be obtained either by flexure of the bracket, the shaft, or bearing springs (in the spring-type bearing).

Figure 3 shows a representative thrust block and retaining ring. It is in the shaft back of the groove that all the tensile stresses in the shaft reverse to compressive stresses above the retaining ring. Sketch *A* indicates these stress lines, and it is obvious that the most highly stressed part of the shaft is the fillet at the top of the groove. If the bracket is so stiff that any misalignment must be adjusted by flexure of the shaft, as indicated in sketch *B*, the compressive loads of the retaining ring will all be concentrated on one side as shown in *C* and *C'*, and the load concentration will increase the stress on that portion of the fillet to many times its normal intensity; and as the point of concentration revolves with each revolution of the shaft, this sets up an ideal condition for a fatigue failure. As the thrust collar is usually a slide fit on the shaft, it too will work on its fit, forming rust which further loosens the fit. It is therefore highly undesirable to allow adjustment of the alignment of the thrust-bearing surfaces by bending of the shaft. A reasonable degree of flexibility in the bracket allows the bearing floor to align itself something like *D* and *D'*. This results in heavier loading on one side of the bearing than on the other, but not sufficient to cause concentrated stresses in the retaining ring. Naturally, nothing is completely rigid, and any misalignment will result in flexure of all the parts, shaft, collar, bearing, and bracket. It is desirable that as far as possible the greater portion of the flexure should occur in the stationary parts, such as the bearing and bracket, rather than in revolving parts, such as the shaft and collar; this distribution can be readily obtained by proper design proportions.

A degree of flexibility in the thrust-bearing support will allow a large proportion of the impact vibrations of the water wheels to be absorbed in the mass of the rotor instead of being transmitted undiminished to the babbitted surface of the thrust bearing. These impact vibrations occur in most wheels at certain gate openings; their effect is somewhat like heavy hammer blows on the shaft.

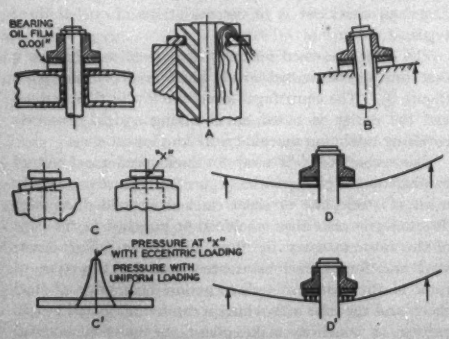


Figure 3. Elements of a typical thrust-block and retaining-ring design

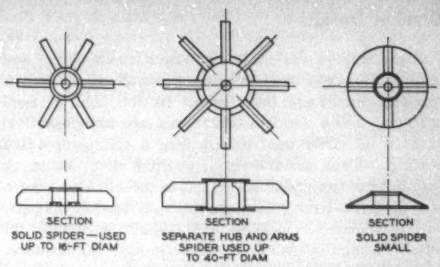


Figure 4. Arrangement of some spider-type brackets

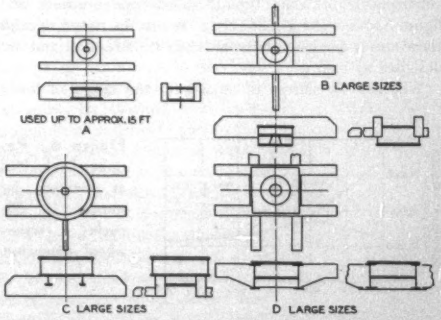


Figure 5. Arrangement of some girder-type brackets

Bracket Design

While still on the subject of gravitational forces and brackets, it might be appropriate to sketch some types of brackets that have been used. In the field of rigid brackets, a few fundamental forms are altogether too rigid to be safely used except with a spring-supported bearing. These are the cone, pyramid, deep domes, or variations of these with panels cut in the surfaces. Some of these forms have been quite generally used in the past, but, fortunately, usually with small machines. In certain forms that can be readily obtained (for instance, domed boiler heads) they are still used, but usually with flexible bearings. Brackets in general use today are of the spider and parallel-girder types. Figure 4 shows the construction of some typical spider-type brackets and figure 5 shows the girder type. It may be noted that all these types are essentially of beam construction and are designed as such.

Whether the thrust is carried by the upper or lower bracket, the design conforms with one of these general arrangements and is usually sufficiently stiff to satisfy the water-wheel manufacturer and sufficiently flexible to mount the thrust bearing properly.

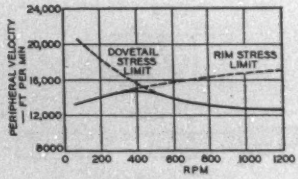


Figure 6. Peripheral velocities as limited by stresses in 60-cycle water-wheel generators

Centrifugal Forces

The revolving part of an alternator is the field, largely because it can be better constructed to withstand centrifugal forces. The two limiting features with regard to centrifugal forces are the dovetail stress (in the base of the poles where they dovetail into the rim of the rotor) and the rim stress. Figure 6 shows the normal limitation in this regard. These limits can be extended by the use of special alloy steels and unorthodox construction, but as yet the water-wheel manufacturers have not produced wheels that exceed these limits, except certain high-speed wheels.

Figure 7 shows limits of maximum feasible kilovolt-ampere ratings of salient-pole generators based on standard construction. When comparing the possible ratings at high speeds with known steam-turbine capacities at these speeds, it must be remembered that water-wheel generators must withstand up to 100 per cent overspeed compared with 10 per cent for a turbine generator; consequently the maximum diameter is $(^{110}/_{200})^2$ or $^1/_3$ and maximum capacity $(^1/_3)^3$ or $^1/_{27}$ of that of a turbogenerator.

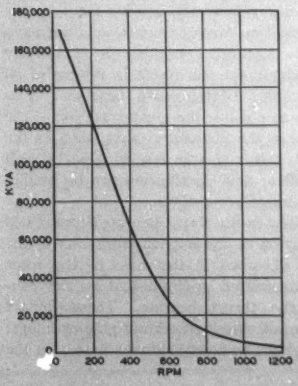


Figure 7. Maximum feasible rated capacity of salient-pole 60-cycle water-wheel generators

Rotor Construction

Centrifugal forces in the revolving parts are of fundamental importance in designing a machine, but as a rule they are not the limiting factors. While the methods of rotor construction are many, present practice on the American continent is to use variations of one of three types.

The first type used for small low-speed machines is a cast-iron or fabricated steel wheel with bolted poles (figure 8). The centrifugal forces are low in these rotors, and the design is based on obtaining a rigid structure requiring minimum machine work and lowest cost.

The second type is used for high-speed machines of medium and large capacities (figure 9). These are usually made of steel plate or sheet stacked as solid disks with dovetail grooves either machined or punched in the edge of the rotor to carry the dovetails of the poles. Cast-steel and forged-steel have been used for this type of rotor in the past, but today the low base price of steel sheet, and the ease with which it can be fabricated by gas cutting or punching makes sheet the most economical material. A laminated rotor is a desirable construction in any event, as centrifugal forces equally divide through

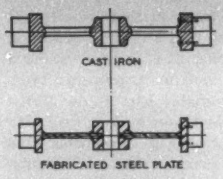


Figure 8. Construction of rotor with cast-iron or fabricated steel wheel

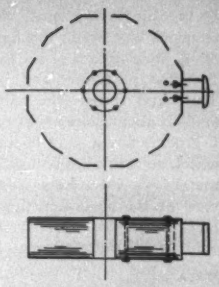


Figure 9 (right). Construction of rotor using stacked steel plates or sheets

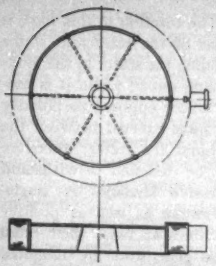


Figure 10 (left). Construction of rotor with laminated rim surrounding a central cast or fabricated steel spider

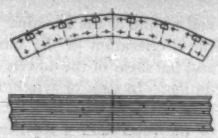


Figure 11. Construction of rim for rotor of figure 10

a number of complete disks. This results in equalization of stresses, and in the isolation of a possible flaw to the particular disk in which it may occur.

The third type of rotor is used for large, medium and low-speed machines. This consists of a laminated rim mounted around a central cast or fabricated steel spider (figure 10). The poles are either bolted or dovetailed to the rim, and the rim carries all the centrifugal forces of poles and rim. The spider is primarily a centering device to locate the rim, carry its weight, and transmit the driving torque to the rim, but carries no centrifugal forces other than that due to its own mass. The rim is made up of a series of segments punched from steel sheet, pinned and bolted together. The efficiency of the rim depends upon the proportion of joint to rim or to the minimum section between dovetails, bolts, holes, etc., and rim section. As the minimum section of a segment comes under a dovetail, the joints are located between dovetails (figure 11). Usual practice is to limit the stress at overspeed to one-third of the ultimate strength of the material used, or two-thirds of the yield point, whichever is lower. This type of rim has the desirable features of the disk-type rotor in that the stresses are equally and uniformly divided among a large number of independent segments, and a flaw in a segment is isolated to that individual segment. The working and rolling that sheet goes through gives sheet steel a uniformity impossible to obtain in castings and most forgings. Shear stresses in the rim are carried by ground steel pins and studs driven through the holes in the rim. Figure 12 is representative of small rotors of this type.

Strain is so intimately associated with stress that it seems proper to indicate here the amount that a rotor expands under centrifugal force even though it is not enough to be of practical significance. It amounts to about five mils per foot of diameter at the overspeed. On the largest machines built to date this does not amount to more than 20 per cent of the air gap and at normal speed, when it might have an effect on the excitation characteristics, it is less than 5 per cent of the air gap.

The poles usually are fastened to the rotor by means of dovetails in the bottom of the poles which are ordinarily of one of two types, V or T. Each of these has its own peculiar virtues, as may be seen in figure 13, which shows both types of construction and how they fail. With both types, unless supported by welding across the bottom surface, failure starts by crumpling of the laminations at the bottom of the dovetails and then tearing in the fillets. The V dovetail is shallower than the T, permitting greater depth of useful rim section, but it has a side wedging action that adds to the rim stress under the dovetail. Hence the proper field of the V dovetail is where the dovetail stresses are low, causing low wedging stresses, and the rim stresses are high thereby securing best utilization of the rim material. The T dovetail has no side thrust, and the long neck stretches sufficiently to equalize the load between dovetails; therefore T dovetails are used singly or in parallel where the pole stresses are high compared with the rim stresses.

No consideration of centrifugal forces would be complete without some reference to unbalance. On the drafting board the rotor, of course, is balanced; however because of variations in thickness of steel and usual tolerances of purchasing or shop practice the rotor may not necessarily be balanced when built. If the rotor is small enough to be assembled and built at the factory it can be balanced there on balancing ways or pivots. In the field it can be balanced in its own bearings by means of special equipment, but this latter method has not much to recommend it. It is a relatively simple matter to balance the spider of the rotor at the factory. The rim punchings can be segregated in groups of segments of the same weight, and piled so that each circle is of punchings of the same weight which should result in a balanced rim. The poles and coils can be individually weighed and located so that they are balanced about the rim. This procedure should produce a balanced rotor, and experience so far indicates that it does.

These are the main problems due to centrifugal forces; there are others—the attachment of all members to the rotor parts, fans, brake plates, coils, coil leads, etc., whirling of oil in the bearing housings, whirling of air in the machine, etc., which are too specific for a general survey.

Magnetic Forces

The other major force is magnetic. The fundamental characteristic of the magnetic pull is that it varies as the square of the flux density. The flux density is determined by the sum of the stator and rotor ampere turns divided

Figure 12. A rotor of the type shown in figures 10 and 11

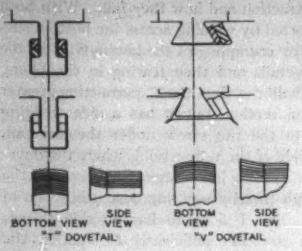


Figure 13. Details of V and T dovetails, and points where failure usually occurs

by the reluctance of the magnetic circuit. This, under normal operating conditions, causes a constant radial magnetic pull between the rotor and stator of about 25 pounds per square inch. If the rotor and stator are concentric circles and the stator and rotor ampere turns are balanced around the periphery, these forces are sustained by compression in the stator core and tension in the rotor rim. However, if the rotor and stator are eccentric, the reluctance will be unbalanced, and there will result an unbalanced magnetic pull that is proportional to the eccentricity, which must be resisted by the guide bearings and the arch and beam strength of the frame. Coils open or short circuited on one side of the core or rotor also will give rise to unbalanced magnetic forces. The design of the guide bearings and their supporting structure is one that must be determined by the extent and probability of occurrence of these unbalanced conditions.

The normal magnetic forces on a generator frame result in compression of the core and frame; like any compression-loaded structure, any unbalanced reaction should be kept within the middle third even though the frame has additional stiffness as a beam. This condition is particularly critical for a force such as magnetic pull which unlike gravity increases directly as the deflection. Thus if a frame is not stiff enough and tends to collapse into, say, an elliptical form, the magnetic forces causing this collapse increase to the extent that stress in the frame increases; consequently the frame will collapse completely against the rotor. Because of this characteristic the frame should be made so that it will collapse to a stronger position if possible. This can be done by securely clamping the core and anchoring it to the frame and doweling the frame to foundation plates anchored in the floor.

In addition to radial pull, there is the torque resulting from the angular displacement of the rotor under load. This displacement is proportional to the load and reacts as a side pull on the poles and coils in the slots. Under normal conditions, this does not amount to much so far as these parts are concerned. If the stator coils are loose in the slots it may cause them to vibrate and become looser, but main strain on the machine comes in case of an instantaneous short circuit or bad synchronizing shot. Under such circumstances the rotor must change its angular position to agree with the new conditions. The force available to do this is limited only by the extent of the reactance of the machine, which limits the stator current, and the force may amount to ten times the normal torque of the machine. The reaction to this force is the acceleration of the inertias of the rotor and stator and the shear of the dowels holding the stator to the foundation. In case of synchronizing out of phase it is possible to have polarity of the stator opposed to polarity of the rotor and a repulsive force exerted between the rotor and stator, tending to burst the stator; therefore any joint in the stator must be designed to withstand bursting as well as compressive stresses. A single-phase short circuit causes negative as well as positive torques which shake the machines at twice their rated frequency. Large single-phase generators are mounted on springs so that the negative forces are absorbed in the vibration of the frame instead of being transmitted to the power house.

Another manifestation of magnetic force is found in the force between coil sides. This varies as the square of the current, attracting when currents flow in the same direction and repelling when in opposite directions. In the slots the coils are surrounded by iron and so are well anchored, but in the end connections they are held mainly by the stiffness of the conductor plus suitable blocking and lashing to prevent dangerous movement.

Natural Frequencies of Vibration

While dealing with gravitational, centrifugal, and magnetic forces, it would be an appropriate time to mention natural frequencies. Any mass acted on by a force that varies with displacement has a natural frequency of vibration. If this natural frequency does not coincide with some forced frequency in the machine no trouble occurs. However, parts that might vibrate at a forced frequency must be checked. These are the upper bracket carrying the rotor vertically against gravity and the shaft bearings and brackets supporting the rotor sideways, which must be checked to see that the critical speed is greater than the overspeed of the unit. Because magnetic pull acts to increase deflection this frequency is lower when the machine is excited than when not excited. The rotor has a torsional natural frequency (when operated on a system) depending on the inertia of the rotor and the displacement angle of the load. Two inertias such as a

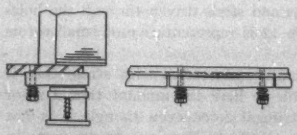


Figure 14. Method of attaching brake shoes to rotor

rotor and flywheel on the same shaft have a natural frequency of oscillation. Other parts, such as fans, core bolts, cover plates, and pipes have natural periods of vibration; if the frequencies of these vibrations coincide with a forced frequency of the generator, such as a harmonic of the speed of revolution or frequency, dangerous stresses or objectionable noises in these parts may result.

Magnetic noise in an alternator is a result of forced vibrations in the audible region, caused by inequalities in

the magnetic circuit. The stator core contains a number of slots, and it is apparent that at a certain slot position the path for most of the flux will be from a pole to the teeth. Thus every time a pole passes a slot there will be a change of this pull from maximum to minimum and back again. The frequency of this variation in pull will depend on the number of slots per pole and will be in the order of 15 to 50 times the line frequency, which is right in the audible range. To prevent this variation in magnetic pull from causing objectionable noise, the pole face should be designed to cause a minimum variation in magnetic pull, and the number of slots should be selected so that a large number of adjacent poles will not exert maximum and minimum pull at the same time, causing the frame to vibrate in distinct nodes.

Figure 15. Portion of a typical rotor showing braking surface

Thermal-Expansion Forces

The other force requiring attention is that resulting from thermal expansion. If constrained, this force, in steel members, amounts to 340 pounds per square inch per degree centigrade rise. If not constrained, the expansion is approximately 0.135 mils per foot per degree centigrade rise. A 30-foot stator frame with an average rise in temperature of 25 degrees centigrade throughout the core will expand a tenth of an inch in diameter. If the frame is held constrained by fixed dowels, high stresses will be exerted on the dowel and the core iron will crumple up in waves around the core. A better method is to dowel the stator radially so that the frame is free to expand radially but remains concentric and is firmly keyed against twisting.

The rotor and stator windings are also subject to strain and stress from differential thermal expansions, and, like the frame, it has been found best to design the insulation and supports so that movement can occur to relieve the stresses. The rotor coils, which are bare copper, take care of themselves if the top collars are strong enough to withstand the coils sliding against them under the pressure of their centrifugal forces. The stator coils, however, are covered with insulation that is relatively cool on the outside but hot enough inside for a coil four feet long to expand about $^1/_{32}$ inch; the insulation must follow the conductor without damage. It has been found that plastic varnish of the asphaltic-base type, when used as sticker between layers of tape, is sufficiently plastic to follow the copper without damage to the insulation.

An interesting example of thermal strains is found in the brake surfaces. This is the surface on the bottom of the rotor against which friction brakes are applied to bring the machine to a quick stop. The friction of braking generates heat that is absorbed by the brake surface, and in the case of a rapid stop the temperature of this surface can easily reach 200 or 300 degrees centigrade before any of the heat can flow into the rim back of the surface (figure 14). This surface tries to expand but cannot if it is part of a solid cold rim, so at the high temperature it is crushed beyond its elastic limit; when it cools, it is stretched beyond its elastic limit. After a number of cycles, cracks begin to appear in the surface. The present solution of this problem is to use small segments and mount them with a spring support so that the plates can expand when hot and return to their original shape when cool. The use of cast iron instead of steel for these surfaces gives better thermal characteristics as well as a superior braking surface. Figure 15 shows such a brake surface.

Mechanical Design Affects Other Characteristics

The foregoing has been mainly a description of how the gravitational, centrifugal, magnetic, and thermal stresses affect the mechanical construction. The mechanical construction in turn affects the electrical and thermal characteristics. Thus while theoretically the D^2L of a machine (D is its diameter and L its length) remains a constant for a certain output and speed through variations of diameter, actually it varies in a series of steps because of the necessity of using an integral number of turns per coil and a suitable number of slots in the stator. The most economical design of generator can be made for those speeds at which the number of poles is divisible by four or six without leaving a factor of three in the answer.

There are certain generator proportions that result in economic electrical design; for instance, the core length should be between one and four times the pole pitch. A shorter core than this, although sometimes necessary in 25-cycle machines, results in a pancake structure that is all frame, spider, brackets, and end connections. Should the required flywheel effect be so large that the electrical proportions are poor, it is usually best to design for the most suitable electrical proportions and obtain the flywheel effect in a separate flywheel. If, however, the required flywheel effect is so low that core length exceeds the four-to-one ratio, it is usually best to design to this ratio, as the difficulties in ventilating a longer core will cost more than the additional rim material.

Cooling

The losses in a generator removed by the cooling air are the resistive (I^2R) losses in the windings and the losses in the core. Bearing losses usually are removed from the

oil by cooling coils in which water is circulated. The losses in a generator usually are limited by the efficiency rather than the heat-dissipating performance, and the size of the machine usually is determined by magnetizing and reactance limitations so the problem of cooling a machine usually devolves into one of dissipating a known

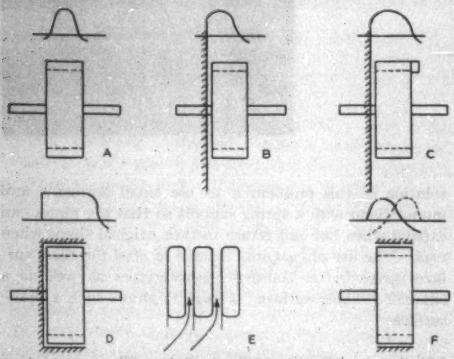


Figure 16. Air-pressure curves for a spinning rotor under various conditions

amount of heat from a machine of a known size. The coolant is air; although water or special gases could be used, the expense is not justified.

It has been almost standard practice to require that the generators be self-ventilating and usually they are. The maximum pressure available to force the air through the core depends upon the peripheral speed of the rotor and the mass of the rotating column of air back of it. Unlike a blower where the air can enter the center and progress radially outward through the blades, in the generator the poles are the blades and the air must enter at right angles to the pressure generated by the rotating surface and again reverse direction to exhaust through the ducts. The ducts are by no means an ideal collector. In essence, the problem of ventilation is one of adding gadgets here and there attempting to turn the generator into a passable blower.

The curve of natural pressure of a rotor spun in open air has a shape like *A*, figure 16. If one end is blocked as shown in *B*, the maximum pressure point approaches that

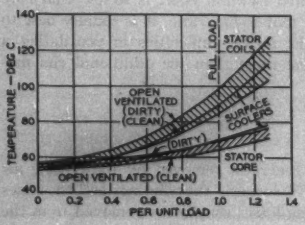


Figure 17. Temperature rises of open-ventilated generators and generators with closed ventilation through surface coolers (based on maximum Canadian ambients)

end and the pressure at the other end becomes negative. If the poles are extended on the negative end as shown in *C*, a positive pressure can be secured over the full length of core. This pressure distribution is not materially changed by placing a core over the rotor provided the ducts are large enough to exhaust all the air that can get in between the poles. If the stator is solid and the end blocked, the pressure curve flattens out and air is recirculated as shown in *D*. Thus by changing conditions it is possible to change the shape of the pressure curve but not its maximum value. Vertical-shaft generators are essentially single-end-ventilated machines like *B*, *C*, and *D*. To obtain a uniform pressure through the core, fan blades can be added to the open end and the exhaust from the high-pressure ducts restricted. This last expedient is undesirable unless it is impossible to secure sufficient air through the open-end ducts by other means such as use of fans, larger ducts at the open end, and throttling of the exhaust through the end connections at the closed end.

As an expedient to reduce the entrance losses between poles and to project the pressure curve toward the open end, fan blades as shown in *E* have been found most effective. Where deep blades are required they work best on alternate poles.

It is possible to get the air to pass through the rotor arms to the closed end of the rotor and shift the point of maximum pressure nearer to the center of the core, but to do this requires scoop blades in the bottom of the rotor to overcome the resistance of the air path through the rotor and around the corners. If this is not done the difference in pressures at the closed end and the open end will prevent any appreciable air from entering the poles from the closed end. The pressure curve shown in *A*, when the rotor is surrounded by a core, is particularly

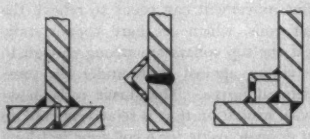


Figure 18. Arrangements for pressure testing of welds for oil-tightness

sensitive to pressure changes on the ends. In a horizontal machine with this type of ventilation the pressure will shift from end to end as shown in *F* by a change in direction of wind unless central interpolar baffles or stabilizing fans are used.

The addition of surface coolers or an elaborate duct system to a generator results in a constant back pressure that must be subtracted from the pressure curve. Consequently to get adequate ventilation through the core, the pressure curve must be flatter than for an open-ventilated machine, and some parts such as the end connections may have to be ventilated separately by means of recirculation and dilution of the cooling air.

The usual temperature limit of a generator is 60-degrees-centigrade rise, and the minimum amount of cooling air is usually set at 100 cubic feet per minute per kilowatt loss, which results in an 18-degree-centigrade rise of the

cooling air. As the total losses will amount to 2⅓ to 5 per cent of the machine rating, the average machine will pass 10 to 20 times its own weight of air through it per day; consequently a very small proportion of dirt in the air may cause quite an accumulation of dirt in the machine. This dirt will form in layers interposed like a sheet of felt between coils and core to be cooled and the cooling air. Consequently a higher temperature is necessary in the coils and core to maintain the same heat flow to the air. A dirty machine usually will be at least 10 degrees centigrade hotter than when clean; a filthy machine may have to be operated at considerably reduced load.

There is no perfect solution of this dirt problem. Where atmospheric conditions are bad, the best solution is to recirculate the air through the machine and surface coolers. This stops the build up of dirt, but the temperature of the cooling air is usually higher than atmospheric; consequently the operating temperature of the machine is higher than that of a clean open-ventilated machine but lower than that of a dirty open-ventilated machine. However, the advantage of a closed ventilating system is not so much in the improvement in the actual operating temperatures as that the temperature rise is considerably lower and that hot spots caused by complete blockage of ducts are prevented.

Figure 17 shows a comparison of temperature and temperature rises in a closed machine with 25-degree water and an open machine with 35-degree air. It may be noted that the main difference lies in the temperature rise of the coils.

In winter, only a part of the cooling air is taken from outside, and the rest recirculated in the powerhouse; hence most of the dirt gets in the machine in the summer. Flies and oil are the two worst offenders in clogging the ventilation of a machine. Flies, lint, and similar fibrous material cling around the sharp edges of the duct like driftwood around a pier and gradually close off the entrance to the ducts. Oil will wet the surfaces of the ducts so that dry dust that would otherwise blow through clings to it, filling the ducts in any place where air velocities are low. For maximum flow through a duct with minimum dirt accumulation, the duct entrance should be made something like a ship's ventilator. This is not practicable, but some improvement has been made by making the wedge to slope into the duct and curving the spaceblock tip in the direction of rotation. Dirt builds up on the edges and surface of this type of duct too, but as the entrance area is larger it does not close them to the same extent.

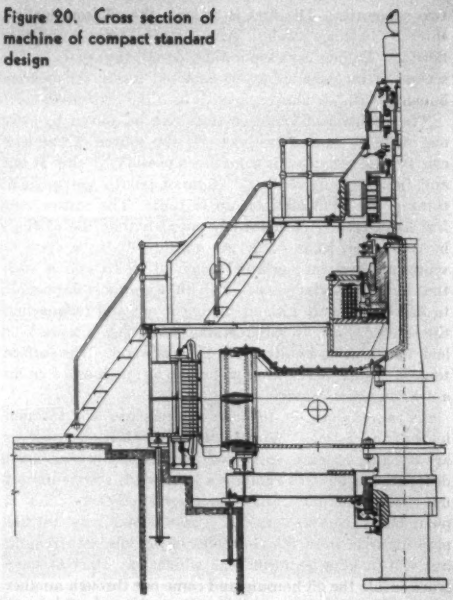


Figure 20. Cross section of machine of compact standard design

Keeping Oil Out of the Windings

How to keep oil out of the windings of machines and in the bearings where it belongs is a problem as old as generators themselves. The problem splits itself into

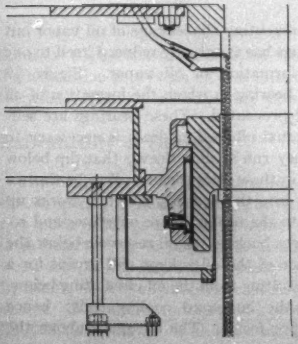


Figure 19. Cross section of bearing in which formation of oil vapor is practically prevented

Figure 21. Two 26,315-kva 180-rpm 60-cycle generators of the type shown in figure 20

two categories: The first is to keep the oil from leaking through castings, welds, gaskets, pipe joints, or overflowing, spilling, or syphoning down the shaft. The second is to keep oil vapor enclosed inside the bearing housing, with air blowing past it into the generator.

The problem of leaky castings can be solved by only one method—sound castings. If the source of the leak can be discovered, it is sometimes possible to chip it out and braze a plug over it. Oilproof paints, galvanizing, tinning, etc., will all open up in time. The reason very few leaks can be permanently cured is that the castings in which the leaks occur are continually in a state of vibration, and the surface tension of oil to iron is such that once the surface is wet with oil it is almost impossible to dislodge the oil without boiling it out and carbonizing the residue. The vibration works the oil out of a crack or leak like working a nail out of a piece of wood. The surface tension is such that the oil will climb as much as a foot up a crack against gravity.

An alternative is to use welded-plate construction instead of castings. Fortunately, the plates themselves are oiltight, at least crosswise; the welds, however, are a different matter. In running a long weld, strains are set up that sometimes cause transverse cracks. This is particularly true in corners. These cracks may not impair the weld from the viewpoint of mechanical strength, but will make a beautiful leak which may start at some crack inside the oil housing and come out through another crack perhaps ten feet away. It may take a week or six months for such a leak to show up, and then drip, drip. After some experience, a technique has been developed that seems to have this problem solved. The first thing is to avoid welding into corners, and the second, to use double oiltight welds. See figure 18. A pipe tap is run into a longitudinal channel cut in the plate, and between the welds. These welds are tested up to and beyond their working stress with hydraulic pressure, which may amount to 1,500 to 2,000 pounds per square inch, and if it holds this pressure for several hours it is considered satisfactory. Sometimes it is easier to weld an angle on the inside and test in the same way.

Gasketed joints below the oil level should be avoided if possible. If necessary, heavy flanges should be used, with closely spaced bolts or studs, and the gasket should be placed on the oil side of the bolt circle (not on both sides as it is quite possible to tighten up on the wrong side). The packing should have characteristics suitable for the job—cork will be satisfactory when no additional load is to be carried, but must be gradually compressed to its final set; for joints that must carry additional load such as exciters, a treated paper-base packing will maintain alignment much better. One of the best methods of sealing is to paint the gaskets and joints with red glyptal paint and dry until tacky and then assemble. This gasket will be destroyed when the joint is separated, but is usually oiltight.

Pipe joints and fittings should be avoided. Where piping is necessary, brass pipe assembled with all screw threads sweated with solder, or copper tube with soldered fittings are the most reliable. Couplings should be of the flange type, and the gaskets treated as previously described.

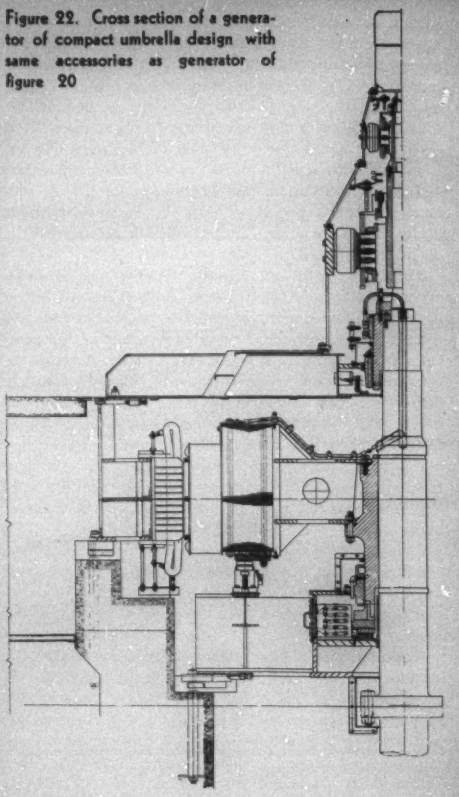


Figure 22. Cross section of a generator of compact umbrella design with same accessories as generator of figure 20

Oil leakage by overflowing, spilling, or syphoning down the shaft can be avoided by proper design of bearing parts, concentricity of the oil tube, and proper venting of the bearing.

The problem of preventing the leakage of oil vapor out of the bearing housings has eventually reduced itself to one of preventing the formation of oil vapor. Figure 19 illustrates a type of bearing in which the formation of oil vapor is pretty well prevented. These bearings are self-lubricating—no external oil feed or drain is necessary to lubricate them. They run against sleeves that dip below the oil level. Holes in these sleeves cause oil to be thrown by centrifugal force into the bearing, where it works up through oil grooves to the top and here overflows and returns through passages back to the oil reservoir below the oil level. The surface of the oil is kept still except for a certain turbulence resulting from the oil circulating below, and quite cool by the immersed cooling coils; hence very little or no vapor forms. The air space above the

oil is vented by a $^1/_{16}$-inch hole, and except for this there is no way for air to get in or out of the bearing housing. As this type of bearing requires no external oil circulation, there are no pipes to leak, no drains to clog with cold oil and overflow the bearings, nor similar troubles.

Oil may be considered in the same light as an explosive—highly necessary where required, but a potential danger any place else. The duty required of oil for the bearings of a vertical-shaft generator is no more severe than in the ordinary ring-lubricated journal bearing, and the same degree of care of the oil should suffice. Oil-circulating systems introduce a hazard to the rest of the machine that is hard to justify on the basis of oil maintenance. Dust in an open-ventilated machine cannot be prevented, but if it is not caked on with oil can usually be readily cleaned off. As the greatest obstruction to the air flow occurs at the surface of the core, the first essential in cleaning a machine is to clean off this dust by a brush between the poles. The rest can be readily blown out.

Figure 23. Cross section of 46,625-kva 75-rpm generator of the Beauharnois, Quebec, Canada, hydroelectric plant

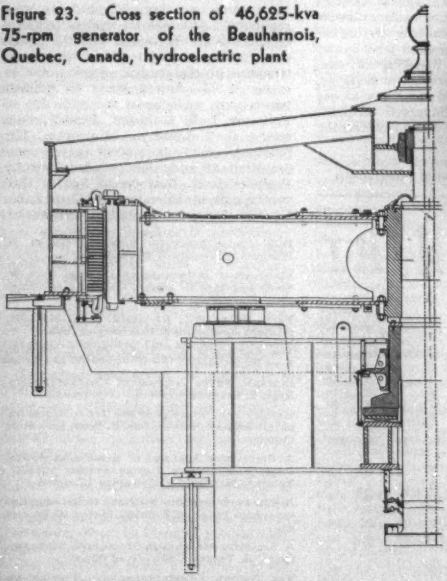


Figure 24. Interior of the Beauharnois plant, with main generators of the type shown in figure 23

Individuality of Design

The arrangement of an alternator as to whether the thrust bearing is mounted above or below, whether one or two guide bearings are used, whether the machine ventilates from the top or bottom, is open ventilated or closed ventilated, is a problem that usually is determined by the hydraulic or civil engineering aspects of the power-house design. The alternator designer's problem is to take the limitations set down for him and make a safe and workable design if possible, and if not to suggest suitable modifications that will result in good design.

Figure 20 shows a compact standard design and figure 21, a view of the installed machine. Figure 22 shows a compact umbrella design with the same number of accessories on top. The only difference is the location of the stator with regard to the coupling face.

Figure 23 shows a section of the 46,625-kva, 75-rpm generator at Beauharnois, Quebec, Canada, and figure 24 an installed view.

An installed view of the 48,500-kva generators at Abitibi Canyon, Ontario, Canada, is shown in the headpiece of this article. These machines have a complete air-circulating system.

These illustrations are not intended to portray any significant trend in design. If anything, they indicate the utter individuality of design of generators built by just one company within a short period of time. Certain fundamental problems are common to all vertical-shaft generators and in these there is a certain continuity of progress of solution as experience and research supply the designer with a better appreciation of the factors of the problems and as advances in technology open avenues of promising construction methods. The other problems are usually peculiar to the particular generator under consideration. As each power site has individual characteristics, such an important item in the development as the generators must be moulded to best fit the power-house requirements.

News
Of Institute and Related Activities

Great Lakes District Holds Sixth General Meeting at Minneapolis

FOR the sixth general meeting of the Great Lakes District, held at the Nicollet Hotel in Minneapolis, Minn., September 27–29 inclusive, the Minnesota Section served as host. Although a majority of the approximately 90 members of this Section reside in the St. Paul-Minneapolis metropolitan area, the Section territory embraces not only all of the state of Minnesota but a double tier of the ten northwesterly counties of Wisconsin. The District itself embraces the six states of Michigan, Indiana, Illinois, Iowa, Wisconsin, and Minnesota, and its "center of gravity" of membership in so far as members are concerned is in the vicinity of Chicago, some 400 miles south and east of Minneapolis. Considering this factor of distance, and considering also the American Legion convention in Chicago and the utilities convention in Indiana held the same week, the total attendance of 230 at Minneapolis, including 141 from outside the Section territory, constituted a worthwhile achievement in the opinion of observers, especially in view of the unusually high percentage of attendance at the several very active student and technical sessions.

Attendance at technical sessions ranged from 55 to 110, averaging about 80. All such sessions were held during the forenoon —two in parallel on each of the first two days; the afternoons being devoted to inspection trips and other activities.

President Farmer spoke briefly before both the student and the general session groups, commenting on various aspects of Institute activities and pointing out the opportunities for professional as well as individual development provided within their scope. As general chairman of the District meeting committee, Dean A. H. Lovell of Ann Arbor, Mich., vice-president for the Great Lakes District, took an active part in all activities. A representative from the office of Governor Harold E. Stassen presented a message of welcome at the opening session.

Principal feature of the entertainment program was a dinner and dance held Thursday evening at the headquarters hotel, attended by 169 members and guests. Following the dinner and preceding the dancing, Doctor Phillips Thomas, research engineer of the Westinghouse Electric and Manufacturing Company, gave an hour's animated lecture demonstrating some of the products and discoveries of the research laboratories. A group of about 36 took advantage of a 90-mile sight-seeing tour around Minneapolis, St. Paul, and vicinity Wednesday afternoon, joining some 65 others for dinner that evening at the country house of the Automobile Club of Minneapolis at Bloomington-on-the-Minnesota.

Doctor William Austin O'Brien, noted pathologist of the University of Minnesota, addressed an audience of about 100 gathered for a Wednesday noon luncheon held at the Hotel Nicollet in conjunction with the Minneapolis Engineers Club and the St. Paul Engineers Society. Doctor O'Brien drew attention to the close similarity in the basic characteristics of students starting out for a career either in modern medicine or electrical engineering. Speaking of electrical equipment in the service of medicine, Doctor O'Brien described the X-ray as one of the greatest known diagnostic facilities, and one also important in certain treatments.

Analysis of Registration at Minneapolis

Membership 8/1/39	Sections	Members	Enrolled Students	Men Guests	Women Guests	Totals
126	Central Indiana	6	6	0	1	13
733	Chicago	16	7	5	1	29
98	Fort Wayne	5	1	0	0	6
67	Iowa	9	4	0	0	13
65	Madison	6	6	3	3	18
358	Michigan	7	3	0	0	10
270	Milwaukee	8	8	1	2	19
80	Minnesota	43	15	14	17	89
77	Urbana	6	3	1	0	10
		106	53	24	24	207
From Outside District 5						
56	Nebraska	0	1	0	0	1
3,355	New York	6	0	1	1	8
517	Pittsburgh	5	0	0	0	5
403	Schenectady	4	0	0	0	4
153	Seattle	1	0	0	0	1
	Non-Section Territory	2	2	0	0	4
		18	3	1	1	23
Totals		124	56	25	25	230

He mentioned the use of the photoelectric cell for close and accurate color comparison in the analysis of solutions, and mentioned as the most ingenious class of equipment the whole range of electrically lighted "scopes" by means of which the modern medical practitioner is able actually to look inside the human body.

Inspection trips supplementing the technical program included visits to several of the large local flour mills, various plants and system facilities of the Northern States Power Company, manufacturing establishments such as those of The Electric Machinery Company, The Minneapolis-Honeywell Heat Regulator Company, the Minnesota Mining and Manufacturing Company, and, of course, the campus of the University of Minnesota including the enormous new hydraulics laboratory at St. Anthony's Falls of the Mississippi River right in the heart of the city.

Student Technical Sessions

In spite of the fact that many of the schools in the District were not fully in operation for the fall term by the time of the Minneapolis meeting, 56 students were registered. Although the student technical session was held in parallel with the Thursday morning general technical session, attendance at the student meeting was in excess of 75. Arrangements for student papers were made under the leadership of Professor J. H. Kuhlman, Branch counselor at the University of Minnesota. The following group of student papers was presented at a session presided over by Professor J. H. Bowman of Purdue University, current chairman of the Great Lakes District committee on student activities:

High Field Electron Emission, **Conrad H. Hoeppner**, University of Wisconsin.

Modulation of Incandescent Lamps, **John W. Smith** and **Max D. Liston**, University of Minnesota.

Fetal Heart Beat Recorder, **W. C. Morrison**, graduate student, State University of Iowa.

The Automatic SOS Alarm, **Paul L. Schmidt**, Iowa State College.

Electric Fence Controller Characteristics, **Roger E. Schuette**, University of Wisconsin.

History and Problems of the Rural Electrification Administration, **Dale H. Scott**, Iowa State College.

A Statistical Analysis of Electrical Power Production in the United States, 1925–37, **Robert E. McDonald**, University of Minnesota.

A New Insulator and Its Place in Present Engineering Practice, **J. Sukup**, Marquette University.

A Ballistic Meter for Measuring Time and Speed, **H. Toomin**, University of Illinois.

The Theory, Construction, and Test of an Icosahedron Photometer, **R. J. Diefenthaler**, University of Illinois.

Tensors for Electrical Engineers, **Vernon Tollefsrud**, University of Minnesota.

Nomography for Electrical Engineers, **G. Ferraro**, University of Detroit.

The Advantages of the Co-operative System of Engineering Education, **J. Price**, University of Detroit.

The following student papers were presented by title only inasmuch as the authors were not present:

A New Electronic Voltage Regulator, **A. V. Donnelly**, State University of Iowa.

Problems in Facsimile Design, **Robert E. Holtz**, University of Wisconsin.

NYA as Viewed by an Engineering Student, **F. A. Glassow**, University of Wisconsin.

Economic Cornice Lighting From Single Large

LAMPS, W. M. Lomonosa and H. H. Hayes, graduate student, University of Michigan.

A SIMPLE GRAPHICAL METHOD OF FINDING THE ILLUMINATION VALUES FROM TUBULAR RIBBON, AND SURFACE SOURCES, E. H. Wakefield, graduate student, University of Michigan.

CONFERENCE ON STUDENT ACTIVITIES

To serve as a medium of exchange for Student Branch operating experiences, and for the purpose of discussing District plans for student activities during the forthcoming academic year, a luncheon conference was held Thursday noon. In effect this was a joint meeting of the Great Lakes District committee on student activities and representatives from Student Branches in the District.

Among the Branch activities reported upon by various student chairmen, the following appeared to bear the stamp of success: Occasional inspection trips to points of technical interest; joint meetings between two or more Branches for competitive presentation of student papers; occasional social meetings; electrical-engineering "shows," frequently for the benefit of the general public. The reports indicated that technical papers presented at Branch meetings by students are becoming more popular and effective, although opinion was not unanimous. Such a trend was emphasized by some as being of particular importance to the individual student as well as to the strength of the Branch as a whole. One Student Branch has a football team.

Considerable discussion concerning the character of Branch membership revealed that within the District the percentages ranged all the way from 10 per cent national and 90 per cent "local" to 75 per cent national and 25 per cent local. The consensus of those most experienced in the conduct of Student Branch affairs was strongly in favor of placing the emphasis on the regular enrollment of student members instead of on the so-called local members.

The group took action in support of a 1940 District student conference, probably some time in October, the matter of place, date, and other arrangements being left to the executive committee for subsequent determination.

Action was taken to ask the AIEE committee on Student Branches to make a further study into the matter of possibly extending the period of time after graduation during which an Enrolled Student may transfer to full membership.

For three-year terms of service on the executive committee of the District committee on student activities, Branch Counselor G. F. Corcoran of the University of Iowa was elected to take office retroactively as of August 1, 1939, and Branch Counselor R. R. Benedict of the University of Wisconsin was elected to take office August 1, 1940.

Of the 17 Student Branches in the Great Lakes District, 16 were represented at the conference by a total of 34 faculty or student members, of which the following constituted the official delegates:

Student Branch Counselors and Alternates

Armour Institute of Technology, Chicago, Ill., E. H. Freeman

Detroit, University of, Detroit, Mich., H. O. Warner

Illinois, University of, Urbana, Ill., E. A. Reid

Iowa State College, Ames, Iowa, B. S. Willis

Iowa, University of, Iowa City, Iowa, G. F. Corcoran

Marquette University, Milwaukee, Wis., E. W. Kane

Michigan College of Mining and Technology, Houghton, Mich., G. W. Swensen

Michigan State College, East Lansing, Mich., M. M. Cory

Michigan, University of, Ann Arbor, Mich., S. S. Attwood

Milwaukee School of Engineering, Milwaukee, Wis., E. L. Weidner

Minnesota, University of, Minneapolis, Minn., J. H. Kuhlman

Northwestern University, Evanston, Ill., A. B. Bronwell

Purdue University, Lafayette, Ind., J. H. Bowman

Rose Polytechnic Institute, Terre Haute, Ind., C. C. Knipmeyer

Wisconsin, University of, Madison, Wis., R. R. Benedict

Not Represented

Lewis Institute, Chicago, Ill.

Notre Dame, University of, Notre Dame, Ind.

Student Branch Chairmen and Alternates

Armour Institute of Technology, Chicago, Ill., A. F. Veras

Detroit, University of, Detroit, Mich., John C. Price

Illinois, University of, Urbana, Ill., Robert M. Sinks

Iowa State College, Ames, Iowa, Richard P. Percy

Iowa, University of, Iowa City, Iowa, Francis L. Ohmer

Marquette University, Milwaukee, Wis., Joseph A. Morley

Michigan College of Mining and Technology, Houghton, Mich., G. M. Myron

Michigan State College, East Lansing, Mich., R. F. Schulte

Michigan, University of, Ann Arbor, Mich., W. R. Powers

Milwaukee School of Engineering, Milwaukee, Wis., R. J. Ungrodt

Minnesota, University of, Minneapolis, Minn., Robert MacDonald

Northwestern University, Evanston, Ill., R. J. Malone

Notre Dame, University of, Notre Dame, Ind., J. A. Varga

Purdue University, Lafayette, Ind., J. E. Nitsche

Rose Polytechnic Institute, Terre Haute, Ind., Willard Louthen

Wisconsin, University of, Madison, Wis., L. A. Burton

Not Represented

Lewis Institute, Chicago, Ill.

Others of the total of 40 persons attending the conference included President F. M. Farmer, Vice-President A. H. Lovell, National Secretary H. H. Henline, District Secretary A. G. Dewars, Secretary M. S. Coover of the AIEE committee on Sections, and Editor G. R. Henninger. Counselor B. S. Willis of Iowa State College presided.

DISTRICT EXECUTIVE COMMITTEE MEETING

At the meeting of the District executive committee Friday afternoon, September 29, K. A. Auty, Chicago, Ill., was unanimously re-elected District treasurer, and T. G. LeClair, Chicago, selected again as District delegate on the national nominating committee of the Institute. K. L. Hansen, Milwaukee, Wis., was nominated for vice-president of the Institute representing District 5, for the two-year term beginning August 1, 1940.

By action of the executive committee, the following will constitute the District coordinating committee for the year ending August 1, 1940:

A. H. Lovell, Michigan, vice-president
A. G. Dewars, Minnesota, secretary
B. S. Willis, Iowa, chairman of committee on student activities
J. J. Shoemaker, Michigan, vice-chairman, AIEE membership committee
A. J. Krupy, Chicago
H. W. Anderson, Iowa
I. B. Garthus, Minnesota
H. T. Kubiak, Madison

The advantages of setting up a separate committee to encourage transfers to higher grades of membership, as opposed to the practice employed by many Sections of delegating that responsibility to the membership committee were discussed by the committee. Although no action was taken, opinion seemed to favor the idea of a separate committee. The matter was regarded as one for local action by Sections, rather than for executive committee ruling.

The question of possible increase in the time interval allowed for transfer from Enrolled Student to Associate without payment of entrance fee was also discussed by the committee. National Secretary Henline explained that at one time the period was one and a half years after graduation, but pointed out that the percentage of transfers under that plan was 35 per cent, as compared to from 50 to 60 per cent under the present plan. A change in the Constitution would be necessary to alter the present plan, he said. No action was taken. Official attendants at the meeting included the following:

Great Lakes District, A. H. Lovell, vice-president; A. G. Dewars, secretary
AIEE Membership Committee, J. J. Shoemaker, District vice-chairman
Central Indiana Section, R. A. Scholl, secretary
Chicago Section, A. J. Krupy, chairman; F. V. Smith, secretary
Fort Wayne Section, F. H. Fleischer, chairman; C. R. Atkinson, secretary
Iowa Section, H. W. Anderson, chairman
Madison Section, H. J. Kubiak, secretary
Michigan Section, W. G. Knickerbocker, chairman
Milwaukee Section, L. T. Rosenberg, chairman
Minnesota Section, I. B. Garthus, chairman; K. J. Mertz, secretary
Urbana Section, G. H. Fett, chairman; C. A. Schille, secretary

President Farmer, National Secretary Henline, and Editor G. R. Henninger also attended.

Record of Attendance at Great Lakes District Meetings

Minneapolis, Minn.	September 1939	230
Lafayette, Ind.	October 1935	437
Milwaukee, Wis.	March 1932	552
Chicago, Ill.	December 1929	600
Chicago, Ill.	November 1927	900
Madison, Wis.	May 1926	180

Future AIEE Meetings

Winter Convention
New York, N. Y., January 22–26, 1940

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Place and date to be announced

Middle Eastern District Holds Tenth General Meeting at Scranton

SCRANTON, center of the northeastern Pennsylvania anthracite region, was the scene of the tenth general meeting to be held by the Middle Eastern District. This was the second such meeting to be sponsored by the Lehigh Valley Section, another having been held in Bethlehem, Pa., in April 1927.

C. T. Sinclair of Pittsburgh, Institute vice-president for the Middle Eastern District, in speaking before the opening general session called attention to the fact that the Middle Eastern District embraces a strip of territory extending eastward from the Indiana boundary to the Atlantic coast and embracing the states of Ohio, West Virginia, Pennsylvania, Maryland, Delaware, and New Jersey with the exception of territory within the circle of 50-mile radius comprising the New York City District. He called attention also to the relatively scattered nature of the Lehigh Valley Section territory, the members of which are distributed among some 34 towns and cities ranging in population from 167 to 143,400, 16 of more than 12,000 and averaging about 51,000, 18 of less than 12,000 and averaging about 3,200. He credited the Lehigh Valley Section as being the first such "area" Section to hold Section meetings in rotation in the several larger cities of its territory, emphasizing that the Section over a period of years had carried on this program with notable success. Chairman E. F. DeTurk of the general committee presided at the opening session, and a representative of Mayor Fred Huester of Scranton was quite generous in proffering the city's keys and other facilities.

The total registered attendance of 313 at the Scranton meeting compares not unfavorably with the over-all average of 380 for the preceding nine meetings held by the District. In terms of the total registration, the attendance at sessions was relatively low, ranging from 30 to 100 and averaging just about 50. These figures undoubtedly reflect the fact that inspection trips were offered during session hours and the further fact that there were no student technical sessions. The total student registration was more or less normal, but aside from those who came to attend the District conference of Student Branch officers, the students came primarily to attend the testimonial luncheon given Thursday noon at the Hotel Casey in honor of Past-President Charles F. Scott, founder of AIEE Student Branch activities. The student group also participated in inspection trips, but did not to any appreciable extent attend the technical sessions.

Supplementing the technical sessions, generous inspection-trip facilities were offered by the Marvine anthracite coal mines of the Hudson Coal Company, the headquarters building of the International Correspondence Schools, the Wallenpaupack hydroelectric plant of the Pennsylvania Power and Light Company at Hawley, the Hazard insulated-wire works of the Okonite Company at Wilkes-Barre, and the Stanton steam plant jointly owned and operated by the Scranton Electric Company and the Pennsylvania Power and Light Company. The coal mines drew by far the largest number of visitors.

The big feature of the non-technical part of the program turned out to be the testimonial luncheon in honor of Doctor Scott. According to Chairman A. S. Mickley of the Lehigh University Student Branch, the day, October 12, was the anniversary date of the founding of the initial Student Branch at Lehigh University in 1902. An outline of Doctor Scott's early educational background was given by Dean W. M. Young of Ohio University, and Doctor Scott's professional career and activities were traced by Professor F. C. Caldwell of Ohio State University. In responding, Doctor Scott effectively emphasized to his listeners, among which were many students, that there is in effect just as much challenge and opportunity in the future before the young men of today as there was in the future before the young men of the past, and that individual initiative is just as valuable now as it ever was. He urged his listeners to look forward rather than to spend too much time looking backward, stating that "experience of the past is of value and worthy of recognition only in so far as it contributes to our present and future development."

A stag smoker held Thursday evening, October 12, drew an attendance of about 100. The program was a combination of a burlesque of an old-time frontier gaming casino and an auction sale wherein the participants were able to use their stage-money winnings for the "purchase" of prizes.

The relatively few women registered were generously entertained. For them there was a luncheon at the Scranton Club, an inspection trip to the International Correspondence School where tea was served, and an evening entertainment at the Jermyn Hotel, all on Wednesday, and on Thursday a bridge-luncheon at the Scranton Country Club.

The closing feature of the entertainment program was the informal dinner and dance that drew 96 to the Hotel Casey Thursday evening. Following the dinner and preceding the dance, an address on "Business and World Politics," was given by President Raoul E. Desvernine of the Crucible Steel Company of America, New York. The speaker sought to dispel the erroneous popular belief that "business men want war," asserting strongly that "just the contrary is true, because business as a whole has recognized and has had occasion to remember that new wars bring new regimentation and new controls for business and industry that never are wholly withdrawn afterward." Mr. Desvernine emphasized further that "business has its responsibilities to government and government has its responsibilities to business. The latter are just as imperative as the former if we are to be prepared to meet the exigencies of the moment and if we are to justify the efficiency of political and industrial democracy as a practical way of life in the face of a world challenge."

District Executive Committee Meets

With 10 out of 13 Sections represented, the District executive committee held a busy all-afternoon session October 11. District Vice-Chairman M. B. Wyman of the national membership committee reported more than 180 new members for the District since May of this year, and commented upon proposals to improve the scope and character of membership activities. There ensued an excellent example of the purpose for which such meetings are held—a generous exchange and constructive discussion of various ideas from and experiences of the different Sections. There was an extended discussion of the relative merits of the area Section plan such as that followed by the Lehigh Valley Section with rotated meetings, as against the plan of Section subdivision such as represented by the creation of the Mansfield Section from within the Cleveland Section territory. Opinions differed.

The matter of prize-paper competition within the District was reported upon by Professor A. G. Ennis of Washington, D. C., chairman of the District prize awards committee: So far this year two student papers and five other papers have been submitted. By action of the executive committee, the prize awards committee personnel will remain unchanged until February 15, 1940, after all the current year's papers are in, at which time a committee for the following year will be named. Present committee personnel:

A. G. Ennis, Washington, D. C.
F. E. Harrell, Cleveland
W. B. Morton, Philadelphia
E. W. Oesterreich, Pittsburgh
B. Van Ness, Jr., Baltimore

By action of the executive committee, the personnel of the District co-ordinating

Analysis of Registration at Scranton

Membership 9/1/39	Sections	Members	Enrolled Students	Men Guests	Women Guests	Totals
75	Akron	2	4	2		8
180	Cincinnati	4				4
298	Cleveland	6				6
95	Columbus	6	4			10
65	Erie	3			2	5
191	Lehigh Valley	61	12	22	11	106
224	Maryland	8	6	1		15
610	Philadelphia	21	6	16	3	46
517	Pittsburgh	21	5	2	3	31
86	Sharon	2				2
78	Toledo	1	1	1		3
332	Washington	3	1	1		5
	Non-Section Territory		1	1		2
		138	40	46	19	243
From Outside District 2						
126	Central Indiana		3	3		6
733	Chicago		1			1
265	Connecticut	1				1
51	Ithaca	3	1	1	3	8
3,355	New York	21	7	4	3	32
178	Pittsfield	6		1		7
91	Providence	1				1
403	Schenectady	8	2	2	1	12
58	Worcester	1		1		2
		41	5	14	10	70
Totals		179	45	60	29	313

committee for the forthcoming year will be:

C. T. Sinclair, Pittsburgh, vice-president
W. J. Lyman, Pittsburgh, District secretary
L. R. Culver, Cincinnati, chairman of committee on student activities
R. W. Prince, Washington
S. S. Seyfert, Lehigh Valley
V. G. Rettig, Cincinnati
M. S. Schneider, Cincinnati

To form the District meeting committee, the foregoing list will be augmented by:

A. C. Burroway, Cincinnati
E. S. Fields, Cincinnati

For the dates of the District meeting scheduled for 1940 in Cincinnati, the Cincinnati Section representatives recommended October 9–11 as first choice and November 6–8 as second choice (the Student Branch counselors subsequently took action favoring the earlier date). Final decision was left to the District meeting committee.

A strong bid for the holding of the 1941 AIEE winter convention in Philadelphia was made by the representatives of the Philadelphia Section, with the support of the District's past vice-president, I. Melville Stein. After considering information as to the adequacy and suitability of facilities for hotel accommodations, meeting rooms, technical inspection trips, entertainment activities, and after reviewing the success of the 1924 winter convention as held in Philadelphia, the executive committee took unanimous action endorsing the proposal.

There was some discussion of the proposed model law for the registration of engineers, and suggestions for vice-presidential visits to Sections and Branches. Past-Vice-President I. Melville Stein was selected as Middle Eastern District delegate to the national nominating committee meeting that probably will be held during the forthcoming winter convention.

Official attendants at the executive committee meeting were as follows:

Middle Eastern District, C. T. Sinclair, vice-president; W. J. Lyman, secretary
AIEE membership committee, M. B. Wyman, vice-chairman
Akron Section, T. F. Brandt, chairman
Cincinnati Section, M. S. Schneider, chairman; V. G. Rettig, secretary
Cleveland Section, H. J. Dible, chairman; J. C. Strasbourger, secretary
Columbus Section, not represented
Erie Section, W. D. Bearce, secretary; J. D. Heibel, alternate for chairman
Lehigh Valley Section, J. E. Treweek, secretary
Mansfield Section, not represented
Maryland Section, H. A. Frey, chairman
Philadelphia Section, E. P. Yerkes, chairman; W. B. Morton, secretary
Pittsburgh Section, R. W. Oesterreich, chairman
Sharon Section, not represented
Toledo Section, J. S. Sawvel, chairman
Washington Section, A. G. Ennis, alternate for chairman

Others present included Past-Vice-President I. Melville Stein, Philadelphia, Pa., President F. M. Farmer, and Editor G. R. Henninger, New York, N. Y.

Student Branch Counselors Confer

Counselors of the Student Branches of the Middle Eastern District held an all-morning session at Scranton, Thursday, October 12. This group selected Professor L. R. Culver of Cincinnati to serve for the ensuing year as chairman of the District committee on student activities. In accordance with District custom, the retiring chairman, Professor E. E. Kimberly of Columbus was selected to serve for the same period as secretary, taking the place of the retiring secretary, Professor A. G. Ennis of Washington. The group also decided to hold the 1940 District conferences of Branch counselors and student officers in conjunction with the District meeting scheduled to be held in Cincinnati, probably in October.

A lengthy discussion and exchange of experiences incidental to the problem of developing student papers led to the adoption of a proposal endorsing the sentiments expressed at the 1939 summer convention conference, to the effect that a suitable standard award be adopted by the Institute in lieu of the present system of cash prizes for student papers. General sentiment was strongly to the effect that a medal, plaque, or other suitable trophy would be of much more lasting interest and value than any feasible cash prize which at best soon is spent and forgotten. Several problems of a local nature received attention also. Attending were the following official representatives:

Student Branch Counselors and Alternates

Akron, University of, Akron, Ohio, J. T. Walther
Bucknell University, Lewisburg, Pa., J. B. Miller
Case School of Applied Science, Cleveland, Ohio, J. R. Martin
Cincinnati, University of, Cincinnati, Ohio, L. R. Culver
Drexel Institute of Technology, Philadelphia, Pa., E. O. Lange
George Washington University, Washington, D. C., A. G. Ennis
Johns Hopkins University, The, Baltimore, Md., W. B. Kouwenhoven
Lafayette College, Easton, Pa., F. W. Smith
Lehigh University, Bethlehem, Pa., W. H. Formhals
Maryland, University of, College Park, Md., L. J. Hodgins
Ohio Northern University, Ada, Ohio, D. S. Pearson
Ohio State University, Columbus, Ohio, E. E. Kimberly
Ohio University, Athens, Ohio, W. M. Young
Pennsylvania State College, State College, Pa., P. X. Rice
Pennsylvania, University of, Philadelphia, Pa., Irven Travis
Pittsburgh, University of, Pittsburgh, Pa., H. E. Dyche
Princeton University, Princeton, N. J., A. E. Vivell
Swarthmore College, Swarthmore, Pa., J. D. McCrumm
Villanova College, Villanova, Pa., H. S. Bueche
West Virginia University, Morgantown, W. Va., A. H. Forman

Not Represented

Catholic University of America, Washington, D. C.
Carnegie Institute of Technology, Pittsburgh, Pa.

Branch Officers Hold Conference

Paralleling the conference of Student Branch counselors, the Branch officers met for the discussion and exchange of experiences concerning various questions relating to branch activities.

A suggestion for securing better attendance at Branch meetings was presented as the practice of the Branches at Carnegie Institute of Technology and Case School of Applied Science, where meetings are held in connection with weekly seminar courses at which attendance is compulsory for members of the junior and senior classes. A similar seminar is held at most of the larger engineering schools. This procedure was questioned by some, however, and was not regarded as generally practicable.

Copies of the *Case AIEE News Sheet*, Branch publication, were distributed and the suggestion made that the paper be developed into a joint publication for all Student Branches in the District, to be printed at Case. It was decided that Branch Chairman Swarthout of Case should investigate possibilities and notify the various Branches, and if possible, the plan should be undertaken.

Attending this conference were the following official representatives:

Student Branch Chairmen and Alternates

Akron, University of, Akron, Ohio, M. A. Yakubik
Bucknell University, Lewisburg, Pa., H. D. Gulnac
Carnegie Institute of Technology, Pittsburgh, Pa., F. S. Adkins
Case School of Applied Science, Cleveland, O., D. K. Swarthout
George Washington University, Washington, D. C., C. G. Kurz
Johns Hopkins University, The, Baltimore, Md., F. H. Kohlhoff
Lafayette College, Easton, Pa., W. M. Piatt
Lehigh University, Bethlehem, Pa., A. S. Mickley
Maryland, University of, College Park, Md., W. H. Watkins
Ohio Northern University, Ada, Ohio, Richard Papenhausen
Ohio State University, Columbus, Ohio, L. R. Kempton
Ohio University, Athens, Ohio, E. C. Barnes
Pennsylvania State College, State College, Pa., H. R. Lloyd
Pennsylvania, University of Philadelphia, Pa., Ernest Boghosian
Pittsburgh, University of, Pittsburgh, Pa., R. A. Warren
Swarthmore College, Swarthmore, Pa., J. W. Kalb
Villanova College, Villanova, Pa., W. E. Kelly
West Virginia University, Morgantown, W. Va., D. T. Worrell

Not Represented

Catholic University of America, Washington, D. C.
Cincinnati, University of, Cincinnati, Ohio
Drexel Institute of Technology, Philadelphia, Pa.
Princeton University, Princeton, N. J.

Others present, in addition to Mr. Henline, were President Farmer, Doctor Charles F. Scott, and Retiring-Chairman E. E. Kimberly of the District committee on student activities.

There were no student technical sessions held in connection with this District meeting although a good many students registered for attendance at the Charles F. Scott testimonial luncheon and for registration in the technical inspection trips.

Record of Attendance at Middle Eastern District Meetings

Scranton, Pa.	October 1939	313
Akron, Ohio	October 1937	464
Baltimore, Md.	October 1932	240
Pittsburgh, Pa.	April 1931	500
Philadelphia, Pa.	October 1930	500
Cincinnati, Ohio	March 1929	270
Baltimore, Md.	April 1928	400
Bethlehem, Pa.	April 1927	400
Cleveland, Ohio	March 1926	430
Washington, D. C.	January 1925	213

Nomination of AIEE Officers for 1940 Election; Members' Suggestions Invited Until December 15

FOR the nomination of national officers to be voted upon in the spring of 1940, the AIEE national nominating committee will meet during the winter convention, January 22–26, 1940. The officers to be elected are: a president, a national treasurer, three directors, and five vice-presidents, one from each of the odd-numbered geographical Districts. Fellows only are eligible for the office of president, and Members and Fellows for the offices of vice-president, director, and national treasurer.

To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1939.

In accordance with the provisions in the constitution and bylaws, as amended during 1935 and quoted in the following paragraphs, actions relative to the organization of the national nominating committee are now under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical district, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical districts; all to be selected when and as provided in the bylaws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical district shall act as a nominating committee of the candidate for election as vice-president of that district, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before January 31 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical districts, if received by the national nominating committee when and as provided in the bylaws; otherwise the national nominating committee shall nominate one or more candidates for vice-president(s) from the district(s) concerned.

Bylaws

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district that by December 15 of that year the executive committee of each district must select a member of that district to serve as a member of the national nominating committee and shall, by December 15, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that district, made by the district executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the national nominating committee shall be published in the March issue of ELECTRICAL ENGINEERING (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in Section 31 of the constitution and Section 23 of the bylaws, which are quoted below:

Constitution

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the by-laws; such petitions for the nomination of vice-presidents shall be signed only by members within the district concerned.

Bylaws

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with Article VI, Section 31 (constitution), must be received by the secretary of the national nominating committee not later than March 25th of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with Article VI of the constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(Signed) H. H. HENLINE,
National Secretary

November 1, 1939

Pump Motors at Eagle Mountain Ready for Service

SYNCHRONOUS pumping motors, each of which delivers 12,500 horsepower at 450 rpm to the vertical pumps, have been installed in the Eagle Mountain and Hayfield pumping stations of the Colorado River Aqueduct. Shown here are the three motors at the Eagle Mountain station, which, with their three duplicates at Hayfield, are said to be the largest pumping motors in the world. They were made by Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. The motors are started directly across 6,900-volt lines fed through transformers from the 230-kv line built solely to carry power from Boulder Dam for aqueduct pumping. Delivery of water to coast cities is expected early in 1940 by the Colorado River project, which includes a diversion and power dam, 150 miles below Boulder Dam, five pumping stations with an aggregate lift of 1,634 feet, and 242 miles of aqueduct. (For Aqueduct details see TRANS., March 1939, pp. 112–23.)

Hoover Medal for 1939 Awarded to Gano Dunn

The Hoover Medal "awarded by engineers to a fellow engineer for distinguished public service" by a joint engineering societies board will be given for 1939 to Gano Dunn (A'91, F'12) president of the J. G. White Engineering Corporation, New York, N. Y., and past-president and Edison Medalist of the AIEE. The award will be formally made during the Institute's coming winter convention, in New York, N. Y., January 22–26, 1940. A biographical sketch of Doctor Dunn appears elsewhere in this issue.

Instituted in 1929 by gift of Conrad N.

Lauer of Philadelphia, past-president of The American Society of Mechanical Engineers, the Hoover Medal has been awarded four times, first to former President Herbert Hoover (HM'29) whose civic and humanitarian achievements it was established to commemorate; to Ambrose Swasey (HM'28) founder of the Engineering Foundation; and to John Frank Stevens, chief engineer of the Panama Canal. Members of the board of award which selected Doctor Dunn, and the societies they represent, were: for the American Society of Civil Engineers, Ralph Budd, A. S. Crane (A'04, M'13), the late Thaddeus Merriman (died September 26, 1939); for the American Institute of Mining and Metallurgical Engineers, C. H. Crane, J. V. W. Reynders, Scott Turner; for The American Society of Mechanical Engineers, W. H. Kenerson, C. N. Lauer, S. F. Voorhees; for the AIEE, H. H. Barnes, Jr. (A'00, F'13), A. W. Berresford (A'94, F'14, past-president), William McClellan (A'04 F'12, past-president).

ECPD Selects Officers and Committees

At its seventh annual meeting held October 20, 1939, the Engineers' Council for Professional Development re-elected J. P. H. Perry, vice-president, Turner Construction Company, New York, N. Y., as chairman, and R. E. Doherty (A'16, F'39) president, Carnegie Institute of Technology, Pittsburgh, Pa., as vice-chairman. C. E. Davies, secretary, The American Society of Mechanical Engineers, was elected secretary of ECPD, and G. T. Seabury, secretary, American Society of Civil Engineers, assistant secretary. United Engineering Trustees, Inc., was reappointed treasurer of ECPD. Chairmen of three committees were reappointed as follows: R. L. Sackett, student selection and guidance; O. W. Eshbach (A'17, F'37) professional training; C. F. Scott (A'92, F'25, HM'29) professional recognition. A. A. Potter was appointed chairman of the committee on engineering schools, and J. C. Arnell (A'28) was reappointed chairman of the junior committee on professional training.

Upon recommendation of the retiring executive committee, the following were reappointed to the executive committee for the ensuing year: E. R. Needles, representing ASCE; G. B. Waterhouse, representing the American Institute of Mining and Metallurgical Engineers; R. E. Doherty (A'16, F'39) representing the Society for the Promotion of Engineering Education. Members newly elected to the executive committee were: A. R. Stevenson, Jr. (A'20, F'37) representing ASME (alternate during 1938–39); J. F. Fairman (A'20, F'35) representing AIEE; B. F. Dodge, representing the American Institute of Chemical Engineers; C. F. Scott (A'92, F'25, HM'29) representing the National Council of State Boards of Engineering Examiners.

Appointments of the following representatives by the various societies for the three-year term 1939–42 were announced: ASCE, F. E. Winsor (reappointment); AIME, W. B. Plank (reappointment); ASME, R. L. Sackett; AIEE, O. W. Eshbach; SPEE, R. A. Seaton (reappointment); AIChE, C. M. A. Stine; NCSBEE, C. F. Scott.

Dean Sackett's committee on student selection and guidance presented a revised draft of the booklet "Engineering—A Career, a Culture," on which work has been under way for the past year or two. The Council accepted the draft; voted unanimously to change the title to "Engineering as a Career," and to submit it for review and criticism to the entire personnel of the governing bodies of the societies of which ECPD is a joint agency.

Doctor Compton's committee on engineering schools reported that, including action at this meeting of the Council, some 687 curricula of 140 degree-granting engineering institutions have been acted upon or are under consideration. Out of 155 such institutions in the United States, 150-odd have asked for inspection. As of October 1938, 678 curricula of 136 schools had been reviewed. A detailed and up-to-date list of engineering curricula accredited by ECPD is expected to be available for inclusion in the December issue of ELECTRICAL ENGINEERING.

The seventh annual dinner of ECPD was held Friday evening, October 29, at the Engineers' Club, New York. Chairman Perry presided and in his opening remarks emphasized the necessity of a "long-range view" toward the development of ECPD, pointing out that such an attitude was particularly significant in trying to develop a program of community interest among seven large participating bodies. The first speaker, A. A. Potter, dean of engineering, Purdue University, incoming chairman of the committee on engineering schools, reviewed the work of the committee, and paid special tribute to the retiring chairman, Doctor Karl T. Compton (F'31) president, Massachusetts Institute of Technology.

D. S. Bridgman of the American Telephone and Telegraph Company outlined the employment and personnel policy and experience of that company, with especial regard to the assimilation of engineering and other graduates. He declared that "observation shows all classes of graduates today to be distinctly better and more broadly trained than was the case with the average of ten years ago."

Doctor E. S. Burdell, director, Cooper Union for the Advancement of Arts and Sciences, New York, spoke on "the development of professional competency" and the place of the engineering school in bringing it about, and stated that in his opinion it was the responsibility of the schools to offer studies assuring broad development. He said that Cooper Union intends to parallel its technical courses for the upper classes with general and philosophical studies of similar rank.

Speaking on the subject "What Becomes of the Engineering Graduate?" R. C. Muir, vice-president in charge of engineering, General Electric Company, Schenectady, N. Y., declared that "engineers not only have, but were fairly successfully serving a definite mission to society," which he defined as making a contribution to the improvement of human life. He also said that the experience of his company showed improvement in the quality of engineering graduates over a 20-year period. He pointed out that technical graduates found their way, according to their own bent, into all activities of the company. Less than ten per cent of engineering graduates, he said, remain in fields of basic technical development; the others are distributed among other operations of equal importance. He expressed the opinion that educators "should give more attention to the 90 per cent."

J. V. Davies Dies; Tunnel Engineer

John Vipond Davies, consulting civil engineer associated with many well-known tunnel projects in the United States and other countries, died October 3, 1939. He was born at Swansea, South Wales, October 13, 1862, educated at Wesleyan College, Taunton, Eng., and the University of London, and engaged in engineering work in steel and mining in England before coming to the United States in 1889. He was for many years associated with the consulting firm of Jacobs and Davies, New York, N. Y., of which he became president in 1917. His engineering activities included railway, subway, and dam construction, in addition to tunnel projects, among the latter being the Hudson River tunnels of the Hudson and Manhattan Railroad, aqueduct tunnels in Mexico, the Moffat tunnel in the Rocky Mountains, and various tunnels under the Hudson and East Rivers for utilities in the New York City area.

He received the Telford Gold Medal of the Institution of Civil Engineers of Great Britain, the Norman Gold Medal and other awards of the American Society of Civil Engineers; was a member of both those and several other engineering societies, and past-president of the United Engineering Societies.

Future Meetings of Other Societies

American Association for the Advancement of Science. Winter meeting, December 27, 1939–January 2, 1940, Columbus, Ohio.

American Institute of Mining and Metallurgical Engineers. 152d annual meeting, February 12–15, 1940, New York, N. Y.

American Physical Society. 230th meeting, December 1–2, Chicago, Ill.

231st meeting, December.

Annual meeting (232d), December 28–30, Columbus, Ohio.

233d meeting, February 22–24, 1940, New York, N. Y.

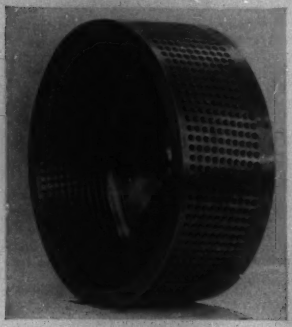
American Society of Civil Engineers. Annual meeting, January 17–20, 1940, New York, N. Y.

American Society of Heating and Ventilating Engineers. 46th annual meeting, January 1940, Cleveland, Ohio.

American Society of Mechanical Engineers. Annual meeting, December 4–8, Philadelphia, Pa.

Société Française des Électriciens. Television meeting, November, Paris, France.

High-Speed Camera to Photograph Electric Arcs



A CAMERA that will take pictures at the rate of 120,000 per second through 1,000 pinhole-sized apertures has been developed by W. K. Rankin, General Electric Company, Philadelphia, Pa. It was designed to photograph electric arcs, thus enabling engineers to study arc behavior in apparatus. Instead of glass lenses, with which reflection from the brilliancy of the arc caused distortion of the image, the camera has holes of 0.01-inch diameter through which light passes to the film. The holes, arranged in ten rows in such a way that no two are exactly opposite each other and no two come into photographic position at the same time, surround a metal drum. The film is placed inside the drum and is held in place by centrifugal force. The drum is revolved by a one-half-horsepower motor capable of 7,200 rpm. As it revolves, each hole passes a slot extending the width of the film, thus exposing an individual picture, nine millimeters square, and the 1,000 pictures which can be taken with a single film are made by one complete revolution. The illustrations show the camera-lens drum and photographs of an arc by the high-speed camera showing changes in arc intensity.

Current Items From American Engineering Council

War Means Changes in U. S. Economy

Although direct participation by the United States in hostilities engaging major European nations now appears remote, a realistic appraisal of the situation indicates that widespread changes directly affecting the American people are logically to be expected.

Two essential factors bearing upon this question are still unsettled. The first is the type of war that is to be fought in Europe—whether it will be an aggressive attempt to force a quick conclusion, or a blockade that will reduce land warfare to a stalemate and rely upon economic isolation to bring about a final settlement. The second consideration is the type of neutrality legislation that will eventually emerge from the debates of the American Congress, and the extent to which trading with actual belligerents will be permitted under its provisions. Each of these decisions will have its effect in modifying the impact of hostilities upon this country, but neither of them can nullify the basic truths that, so long as the war continues, (1) world consumption will be increased because of the wastes of war; (2) world production will be curtailed by the diversion of man-power from factories to armed forces; (3) international trading, particularly with neutral countries, will experience profound changes. As the principal industrial nation not now engaged in war, the United States cannot avoid being affected by these fundamentals.

Many experts discount expectations of an immediate boom in war orders. Pointing out that the pick-up in business that has been experienced since September 1 has been due less to orders from abroad than to domestic stocking-up against the contingency of price increases, they forecast, at the most, a rather gradual and selective volume of foreign purchases in this country during the near future. Eventually, assuming that such buying is legal under the revised neutrality law, it should attain a considerable volume, but its impact upon the American economy is not expected to be sudden.

Of equal importance to the industrialist is the effect of our own preparedness program. Initiated before the outbreak of hostilities in Europe but greatly stimulated thereby, orders relating to national defense from both the government and from private sources are already crowding several industries, notably shipbuilding, aviation, and heavy electrical equipment. As the program authorized by Congress continues to materialize in actual orders the effect upon industry will become more and more apparent.

Another important consideration is the fact that, for the duration of the war, neutral nations that have been buying goods from the belligerent countries will find it increasingly difficult to get deliveries of needed articles. Many will be forced to turn to other sources of supply, and the United States will inevitably receive much of this business.

The cumulative effect of these considerations is the inescapable conclusion that, if the war continues, this country will be called upon for a continually increasing volume of production. This, in turn, will build up payrolls and thus generate increased domestic consumption, adding still more to the demand for goods. How well are we equipped to meet this situation?

Basic factors in industrial production comprise land, capital, plants and equipment, raw materials, labor, power, and transportation. Of land and capital we have an abundance. Current studies indicate that we are now using our industrial equipment at somewhere between two-thirds and three-quarters of its nominal capacity, so that considerable expansion is possible without the necessity for any substantial construction program. The fact that an early peace would dissipate much of the prospective business volume will serve as an additional deterrent against an immediate boom in factory construction except, of course, in specific fields where demand will be concentrated.

As regards raw materials the situation is spotty. Those produced domestically, whether by mining or by agriculture, are generally available in abundance, but those procured from abroad may be limited by complications induced by the war and, specifically, by shortages in shipping. Here generalities are dangerous and each specific commodity must be considered in the light of circumstances. On the whole, however, the situation is not unduly discouraging.

Labor, power, and transportation were the bottlenecks of United States industry during the last World War. Whether history will repeat itself in this respect remains to be seen, although conditions have changed radically and, on the whole, for the better, during the intervening years. But the depression has been a poor preparation period for all three.

Shortages in skilled labor will undoubtedly develop in some lines before industrial production expands very far—in fact, aviation and shipbuilding are already experiencing discomfort in this respect. Although many industries have mechanized their operations to a considerable extent in the last 25 years and are less dependent upon specialized skills, and although even the extreme of American participation in hostilities is expected, according to present mobilization plans, to respect the needs of industry for specially qualified men, the labor problem has the most ominous aspect of any here considered.

The outlook for transportation is somewhat less serious. Broadly speaking the

railroads, which were tied up in knots during the last war, have retained undiminished their capacity for moving goods, and in the meantime an entire new supplement—highway transportation—has developed to serve as a relief valve. Already steps are being taken by the railroads to refurbish and supplement old equipment in anticipation of an increasing volume of traffic.

In considering the power situation two factors must be balanced. On the one hand reserve generating capacity within the utility industry is much higher than it was in 1914; on the other, industry is now much more dependent than it was then upon purchased electric power. An additional cushion is provided by the widespread existence of interconnections between different generating areas, permitting the exchange of power to meet diverse needs. During the last war the difficulty of obtaining coal in adequate quantities was a major source of trouble; now we have many mines that are either closed down entirely or operating much under capacity. This problem concerns both power and transportation, but it should be noted that now it takes only about $1^1/_2$ pounds of coal to produce a kilowatt-hour of electricity, as compared with approximately 4 pounds in 1914. In addition, the elimination of many scattered industrial power plants should do much to simplify the problem of delivering fuel where it is needed. Hydroelectric power is also available in much larger quantities, with much unused capacity available at the various Federal public works projects now approaching completion.

No attempt is made herein to discuss long-term effects of this prospective increase in business volume, nor to consider whether the United States will, in the long run, benefit or suffer from the economic changes that will result. If demands for goods develop in accordance with the conditions discussed above, it is inconceivable that they will not be met to a greater or lesser extent by American industry. But no one familiar with the economic consequences of the last war can fail to realize that any substantial expansion of this country's productive equipment will involve serious problems of readjustment when hostilities finally come to a close and belligerent Europe resumes peaceful production.

Strategic Minerals Sought

As the result of recommendations by the Army and Navy munitions board, the Department of the Interior now has engineering parties at work in seven states investigating possible sources of supply for minerals needed for national defense and not at present produced in sufficient quantities within the United States. Particular stress is being laid upon potential supplies of antimony, chromium, manganese, tin, and tungsten. The investigations are being carried on in Montana, Wyoming, Oregon, Washington, South Dakota, New Mexico, and Nevada.

President Roosevelt has issued a general request to owners of stocks of these and other important strategic minerals not to sell them to foreign purchasers but to hold them for possible use within this country.

Standards

Standards Committee to Study Voltages Below 100

A subcommittee of the standards committee has been organized to study standardization of voltages below 100. The committee at present has eight members under the chairmanship of Professor D. F. Miner of the Carnegie Institute of Technology. In order to obtain representation from all interested fields, it may become advisable to add one or two additional members. It is expected that this Subcommittee will co-ordinate its work with that of an American Standards Association committee to be organized at the suggestion of NEMA for making a similar study.

Voltages below 100 are used much more extensively than most of us realize and it is surprising that national standardization in this range has not been undertaken sooner, all the more so as the International Electrotechnical Commission has been working on an international standard for some years. Their publication No. 38 on "IEC Standard Voltages," recently issued, includes a tabulation of values below 100.

A preliminary survey has been made to obtain data on present practices in the following: central stations, signalling, railways and buses, arc devices and therapeutic, telephones, welding, lighting, portable tools and devices, electronics.

This preliminary survey indicates that there are now in use in the United States 42 well-established voltages in the range 1 to 100 volts. These fall into apparatus classes with preference for certain voltages for certain applications. Further study will be made of the data to determine whether some simplification and standardization is practicable. There appear to be very few existing standards at present even for specific types of apparatus. It may not be possible to adopt standard voltages applicable to all apparatus, but it will be useful to suggest standard values at least for specific apparatus classes, such as signaling, supervisory control, and electronic tubes.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and the other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Why So Few Famous Engineers Today?

To the Editor:

In the presentation of answers to the question indicated in the above title in both Mr. Gannett's article in *Engineering News Record* and in ELECTRICAL ENGINEERING's comments in the October 1939 issue, "famous engineers" rather than "great engineers" are considered. There is a fundamental difference here, and the terms must not be confused. Some of the requirements to make an engineer *famous* do not apply at all in making an engineer *great*. Such, for example, are "salesmanship," "showmanship," "luck," even outward "enthusiasm," although it is conceded that no man grows in his profession without that inward enthusiasm and love for his job which keep him forever at it. An engineer to become great must, above every other quality, possess great ability and great character; in fact these two terms include every other characteristic necessary.

I believe there are at the present time more great engineers than in any previous period in the history of the profession. And perhaps for this very reason there are not many famous in the sense of standing out in the headlines above their fellows and exciting popular imagination. Otherwise how can we account for the Hudson tunnels and bridges; Colorado canyon crossings and Boulder dams; Grand Coulees and the magnificent palaces of the air? Many of the modern engineering feats require the combined brains and skill of several great engineers. Technological progress can no longer depend on an Arthur Morgan or a General Goethals. Engineering projects and completed works have in 20 years become so numerous and so immense and exacting as to require the utmost in character and ability of trained and experienced men. By comparison the bridges of Eads and of the Roeblings and the circuits of Marconi and Pupin pale into virtual insignificance. And yet to engineering minds—even to lay minds—these have become so familiar that they no longer possess the glamor and interest which attached to the fewer accomplishments of possibly lesser minds of former years. Furthermore, the professional spirit and ethics of engineering today curb those elements of character which make for publicity and showmanship justly frowned upon even by the lay public. In short, among the many on the higher levels of ability rarely may one outshine in intelligence and skill. Great works are taken for granted while their designers and builders are of secondary interest or are entirely overlooked.

Literary connoisseurs 50 or 60 years of age are lamenting the absence today of such geniuses as graced the fields of literature in former years. They ask "Where is

there a Shakespeare or a Milton; an Emerson or a Hawthorne?" The conditions are similar to those in engineering, and the answers are in general identical. A misquotation of President Davis, Stevens Institute of Technology, appropriately sums up the situation in engineering: "Engineering itself may (has) become more famous than any of the great personalities" who have made it so.

Very truly yours,

A. A. ATKINSON (A'07, M'27)

(Retired dean, college of applied science, Ohio University, Athens, Ohio)

To the Editor:

Mr. Farley Gannett's query as to the cause of the apparent dearth of individually outstanding engineers today as compared with the number of "giants (engineering) in those days" can be answered, in my opinion, as follows:

In the earlier days of engineering, during the 19th century and the first decade of the present century, there was less specialization in the engineering field than there is today, with the result that an individual engineer wrestled personally with all of the problems of an engineering project, both of theory and of practice, and hence he stood out over his relatively few fellow engineers. The individual engineer's work today is more highly specialized, is in cooperation with the work of many able fellow engineers, and hence, in general, he no longer towers above them, nor does he, as an individual, assume such a prominent position in the public (whether engineering or lay) eye.

To put it otherwise: Formerly we beheld an engineer and his assistants; today we are shown an engineer and his collaborators. The writer was fortunate enough to have had personal contact with some of the engineering giants of former years, but it is his belief that we have engineers now with us of equal ability, who are not so outstanding because there are a larger number of them.

Sincerely yours,

MORTIMER FREUND (A'07, M'12)

(Member of firm, Badie, Freund, and Campbell, consulting engineers, New York, N. Y.)

A New Method of Determining Per Cent Harmonics

To the Editor:

The per cent harmonics in any type of wave is generally determined by the use of the harmonic analyzer or by subjecting the oscillogram of the wave to Fourier analysis. Quite often the harmonic analyzer is not available to the engineer and Fourier analysis leads to tedious efforts. However, in the case where the wave to be analyzed contains only three components or less: for example, fundamental, third, and fifth harmonics, or fundamental, second, and third harmonics, and so on, a method is available by which the per cent harmonics can be readily determined by the use of a voltmeter and ammeter. The following derivation will serve to illustrate the principle.

In general any type of current wave can be represented as:

$$i = \Sigma I_n \sin (n\omega t + \alpha_n) \tag{1}$$

where:

n = whole number indicating the order of the component.
I_n = maximum value of the wave component.
$\omega = 2\pi \times$ fundamental frequency.
α_n = phase angle of the component wave.

If this current flows through a fixed capacitor of zero power factor, the capacitor voltage becomes:

$$e_c = \frac{1}{c}\int i dt$$

$$= -\sum \frac{I_n}{n\omega c} \cos (n\omega t + \alpha_n) \tag{2}$$

The effective value of this voltage is then,

$$E_{c_{eff}} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} e_c^2 dt}$$

$$= \frac{1}{\omega c}\sqrt{\frac{1}{2}\sum\left(\frac{I_n}{n}\right)^2} \tag{3}$$

Since the effective value of any current is defined as

$$I_{eff} = \sqrt{\frac{1}{2}\sum (I_n)^2} \tag{4}$$

equation 3 can be rewritten as:

$$E_{c_{eff}} = \frac{1}{\omega c}\sqrt{\frac{\sum\left(\frac{I_n}{n}\right)^2}{\Sigma (I_n)^2}} \cdot I_{eff} \tag{5}$$

$$\frac{\sum\left(\frac{I_n}{n}\right)^2}{\Sigma (I_n)^2} = \left\{\frac{\omega c \cdot E_{c_{eff}}}{I_{eff}}\right\}^2 = F_c \tag{6}$$

where F_c is measurable.

In the same manner, when the current is made to flow through a pure inductance of constant value, the effective voltage across the inductance becomes:

$$E_{L_{eff}} = \omega L \sqrt{\frac{\Sigma (nI_n)^2}{\Sigma (I_n)^2}} \cdot I_{eff} \tag{7}$$

$$\frac{\Sigma (nI_n)^2}{\Sigma (I_n)^2} = \left\{\frac{E_{L_{eff}}}{\omega L \cdot I_{eff}}\right\}^2 = F_L \tag{8}$$

where F_L is measurable.

The component currents can now be placed in terms of the fundamental such that:

$$I_n = K_n I_f \tag{9}$$

where K_n is the per cent harmonic for the component in question. Substituting equation 9 in equations 6 and 8:

$$\frac{\sum\left(\frac{K_n}{n}\right)^2}{\Sigma (K_n)^2} = F_c \tag{10}$$

$$\frac{\Sigma (nK_n)^2}{\Sigma (K_n)^2} = F_L \tag{11}$$

In the case where the wave is composed of three components there will be just two unknowns, K_{n_1} and K_{n_2}, which are solvable by equations 10 and 11. The lower and higher components can be written respectively as:

$$(K_{n_1})^2 = \frac{(n_2^2 - 1)F_c + \left(1 - \frac{1}{n_2^2}\right)F_L + \left(\frac{1}{n_2^2} - n_2^2\right)}{(n_1^2 - n_2^2)F_c + \left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)F_L + \left(\frac{n_2^2}{n_1^2} - \frac{n_1^2}{n_2^2}\right)} \tag{12}$$

$$(K_{n_2})^2 = \frac{(n_1^2 - 1)F_c + \left(1 - \frac{1}{n_1^2}\right)F_L + \left(\frac{1}{n_1^2} - n_1^2\right)}{(n_2^2 - n_1^2)F_c + \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)F_L + \left(\frac{n_1^2}{n_2^2} - \frac{n_2^2}{n_1^2}\right)} \tag{13}$$

As an illustration when the wave consists of a fundamental, third and fifth harmonics, $n_1 = 3$ and $n_2 = 5$, and equations 12 and 13 reduce to

$$K_3 = \sqrt{\frac{24F_c + .96F_L - 24.96}{-16F_c - .0711F_L + 2.42}} \tag{14}$$

$$K_5 = \sqrt{\frac{8F_c + .999F_L - 8.99}{16F_c + .0711F_L - 2.42}} \tag{15}$$

In the case of a wave with only two components either equation 10 or equation 11 can be used. If equation 10 is used then the per cent harmonic becomes

$$K_n = \sqrt{\frac{F_c - 1}{\left(\frac{1}{n^2} - F_c\right)}} \tag{16}$$

MEASUREMENT OF F_c AND F_L

The values of F_c and F_L may be obtained by measuring separately the current, voltage, and the impedance of the capacitor and inductance at the fundamental frequency. They may also be obtained directly by the following scheme.

Measure the voltage $E_{c_{eff}}$ at a certain value of I_{eff}. Next impress a pure sine wave voltage $E_{c_{sine}}$ on the capacitor and adjust the voltage until the same I_{eff} is obtained. It is obvious from equation 5 or 6 that:

$$F_c = \left\{\frac{E_{c_{eff}}}{E_{c_{sine}}}\right\}^2 \tag{17}$$

In the same manner

$$F_L = \left\{\frac{E_{L_{eff}}}{E_{L_{sine}}}\right\}^2 \tag{18}$$

In conclusion some of the limitations of the method are listed. They are:

1. The method is applicable only to waves containing three components or less.

2. The order of the components present must be known.

3. For accurate results the power component of the two impedances must be small.

Provided these three conditions are satisfied the method outlined enables a rapid calculation of the per cent harmonics.

Very truly yours,

W. T. THOMSON (A'37)

(Instructor in applied mechanics, Kansas State College of Agriculture and Applied Science, Manhattan, Kans.)

Personal Items

Gano Dunn (A'91, F'12) president, J. G. White Engineering Corporation, New York, N. Y., has been chosen to receive the Hoover Medal for 1939, joint engineering-society award, which will be presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. An account of the award appears elsewhere in this issue. Doctor Dunn was born October 18, 1870, in New York, N. Y., and received the degrees of bachelor of science (1889) from the College of the City of New York, electrical engineer (1891) from Columbia University, master of science (1897) from CCNY, and the honorary degrees of master of science (1914) and doctor of science (1938) from Columbia. Employed by Western Union Telegraph Company, New York, as night operator 1886–91, he entered the service of the Crocker-Wheeler Electric Manufacturing Company, Ampere, N. J., in 1891, and from 1898 to 1911 was vice-president and chief engineer. In 1911 he became vice-president of J. G. White and Company and upon the organization of the J. G. White Engineering Corporation in 1913 became its president, a position he has held ever since. From 1916 to 1918 he was a member of the War Department Nitrate Commission, and in 1918 chairman of a joint committee on submarine cables. He was also a member of the engineering committee of the Council of National Defense. In 1936 he represented the State Department at the World Power Conference. He is chairman of the visiting committee of the National Bureau of Standards, and a member of the Patent Office advisory committee, the President's committee on civil service improvement, the Science Advisory Board, and the business advisory board of the Department of Commerce. Since 1935 he has been president of Cooper Union for the Advancement of Science and Art, of which he was formerly a trustee, and he is a trustee of Barnard College and a former alumni trustee of Columbia University. He received the Townsend Harris Medal of the College of the City of New York in 1933 and the Edison Medal of the AIEE for 1937. He has served the AIEE as a manager, vice-president, president (1911–12), member of many committees, and representative on various organizations. He was president of the New York Electrical Society 1900–02, of the United Engineering Societies 1913–16, of the John Fritz Medal Board of Award 1914. He was first chairman of the Engineering Foundation, 1915–16, and chairman of the National Research Council 1923–28. He has been active in international scientific organizations, is honorary secretary for the United States of the Institution of Electrical Engineers, honorary member of the Association of Iron and Steel Engineers, member of the American Society of Civil Engineers, American Society of Mechanical Engineers, Institute of Radio Engineers, American Association for the Advancement of Science, and numerous other scientific societies, and the author of many papers on engineering subjects.

E. W. Allen (A'03, F'22) vice-president, General Electric Company, Schenectady, N. Y., has been appointed chairman of the Institute's Lamme Medal committee for 1939–40. He was appointed to the committee for the term 1938–41. Born in Buchanan, Va., November 9, 1879, he received the degree of bachelor of science in electrical engineering from Virginia Polytechnic Institute in 1900. He entered the testing course of General Electric at Schenectady in January 1901, and was assigned to the engineering department the latter part of the following year. In 1911 he became district engineer with headquarters at Chicago, Ill., and in 1913 was made assistant district manager in addition to his duties as engineer. He was in military service 1917–19, after which he returned to his position at Chicago. He was appointed manager of the company's engineering department at Schenectady in 1924, and vice-president in 1926. He has served on the Institute's education committee and as Institute representative on the United States national committee of the International Electrotechnical Commission.

D. C. Jackson, Jr. (A'23, F'30) has been appointed dean of the college of engineering at the University of Notre Dame, Notre Dame, Ind. Born August 3, 1895, at Madison, Wis., he received the degree of bachelor of arts in scientific studies at Harvard University in 1917 and the degrees of bachelor of science (1921) and master of science (1922) at Massachusetts Institute of Technology in the co-operative electrical-engineering course with General Electric Company. He served in the United States Army 1917–19 as an officer in the Coast Artillery. He was instructor in electrical engineering at the University of Missouri, Columbia, 1922–23 and assistant professor of electrical engineering in charge of electrical-engineering instruction, Trinity College, now Duke University, Durham, N. C., 1923–25. From 1925 to 1930 he was professor and head of the department of electrical engineering at the University of Louisville, Louisville, Ky., and from 1930 to February 1936 held the same position at the University of Kansas, Lawrence. He became director of Lewis Institute, Chicago, Ill., at the beginning of the academic year in 1935, continuing there until 1938. During recent months he has been working with his father, Doctor Dugald C. Jackson (A'87, F'12) on a survey of engineering education conducted by the Engineers' Council for Professional Development. Dean Jackson is a member of the American Society of Civil Engineers, American Society of Mechanical Engineers, and Society for Promotion of Engineering Education.

O. C. Spurling (A'03, M'10) has retired as engineer of plant, Western Electric Company, New York, N. Y. Born September 19, 1874, at St. George's, Bermuda, he was educated there and studied electrical engineering at Pratt Institute and the Chicago School of Electricity. He was employed by Western Electric in New York as a wireman's helper in 1893, and from 1896 to 1898 was engaged in testing for the company in Chicago, Ill., returning to New York as assistant to factory engineer. He was sent abroad in 1902 in charge of design and installation of plants and equipment in London, Eng., and Antwerp, Belgium. After his return in 1905 he assumed charge of building operations at the Hawthorne works of the company near Chicago. Since 1923 he has been engineer of plant, with headquarters in New York, directing construction of the company's factories at Kearny, N. J., and Point Breeze, Baltimore, Md., and other plant expansion. He is a member of The Institution of Electrical Engineers of Great Britain.

J. T. Graff (A'21, M'27) has been appointed assistant vice-president, operation, of the Chesapeake and Potomac Telephone Company, Washington, D. C., handling engineering, plant service, and costs matters. Born December 1, 1877, at Washington, D. C., he received the degree of mechanical engineer from Cornell University in 1900 and was employed by the Western Electric Company, New York, N. Y., the same year. In 1901 he was transferred to the New York and Pennsylvania Telephone and Telegraph Company, Binghamton, N. Y., as wire chief, and in 1902 was again transferred to the Chesapeake and Potomac Telephone Company of Baltimore City, Baltimore, Md. He became district plant supervisor in 1909 and division plant engineer in 1913. From 1917 to 1919 he was in military service, returning to the office of the general

GANO DUNN

D. C. JACKSON, JR.

E. W. ALLEN

H. F. HARVEY, JR.

RAYMOND BAILEY

J. T. GRAFF

plant manager of the Chesapeake and Potomac companies. He was appointed general plant supervisor in 1927, and chief engineer for Virginia in 1935, continuing in that position until his present appointment.

Raymond Bailey (A'17, M'26) assistant electrical engineer, Philadelphia Electric Company, Philadelphia, Pa., has been appointed chairman of the AIEE committee on power transmission and distribution for 1939–40. He has been a member of the committee since 1933, and was vice-chairman 1937–1939. Mr. Bailey was born in Philadelphia May 3, 1894, and was graduated in electrical engineering from Drexel Institute of Technology in 1916. Following graduation he was employed by the Philadelphia Electric Company as an engineering assistant, and in 1918 became assistant chief electrical designer. He was appointed chief electrical designer in 1925 and assumed his present position in 1929. He has also served on the committee on protective devices (chairman 1930–32) and the meetings and papers (now technical program) committee, and as executive secretary of the Middle Eastern District.

H. F. Harvey, Jr. (A'19) electrical engineer, Newport News Shipbuilding and Drydock Company, Newport News, Va., has been appointed chairman of the AIEE committee on applications to marine work for the year 1939–40. He has been a member of that committee and its predecessor, the marine committee, since 1920. Born at Cedar Bridge, N. J., October 12, 1888, he was graduated in electrical engineering from Pratt Institute in 1908. During the next year he was employed by the H. Krautz Manufacturing Company, Brooklyn, N. Y., on design work. From 1909 to 1919 he was employed in the switchboard engineering department of General Electric Company, Schenectady, N. Y., specializing on marine work, particularly electric propulsion of ships. He was employed by the Newport News Company in 1919 as engineer in the electrical division, and is now in charge of all electrical design work on ships.

E. J. O'Connell (A'25, M'36) telephone engineer, American Telephone and Telegraph Company, New York, N. Y., has been appointed chairman of the AIEE committee on communication. He has been a member of the committee since 1931. Born at Chicago, Ill., February 28, 1902, he received the degree of bachelor of science at Northwestern University in 1924. During the following year he was employed by the American Telephone and Telegraph Company on the construction forces building the first telephone cable between New York and Chicago. From 1925 to 1928 he was on the staff of the chief engineer, Illinois Bell Telephone Company, Chicago, and since then has been with the American Telephone and Telegraph Company in New York as technical specialist on protection and inductive co-ordination.

B. R. Teare, Jr. (A'29, M'36) formerly assistant professor of electrical engineering, Yale University, New Haven, Conn., has been appointed to the faculty of Carnegie Institute of Technology, to direct a newly organized program of graduate study in electrical engineering. A native (1907) of Menomonie, Wis., he received the degrees of bachelor of science (1927) and master of science (1928) from the University of Wisconsin and that of doctor of engineering from Yale University. He was employed by General Electric Company, Schenectady, N. Y., from 1929 to 1933, when he was appointed to the Yale faculty. He is a member of the Society for the Promotion of Engineering Education, Sigma Xi, Tau Beta Pi, and Eta Kappa Nu, and has served on technical committees of the AIEE.

Zay Jeffries (M'36) technical director, incandescent lamp department, General Electric Company, Cleveland, Ohio, has been elected to membership in the National Academy of Sciences. Born April 22, 1888, at Willow Lake, S. Dak., he received the degrees of bachelor of science and metallurgical engineer from the South Dakota School of Mines, and the degree of doctor of science from Harvard University. He has been a consultant for the incandescent lamp department of General Electric since 1914, and technical director since 1936. He is a member of the American Institute of Mining and Metallurgical Engineers, American Society of Metals, American Physical Society, Faraday Society, British Iron and Steel Institute, and Institute of Metals.

F. W. Appleton (M'28) has retired as assistant vice-president of the New York (N. Y.) Telephone Company. Born April 12, 1887, at Lake Henry, S. Dak., he received the degree of bachelor of science in electrical engineering from the University of Michigan. He was employed by the New York Telephone Company in 1909 as plant and toll engineer, and has continued with the company ever since, becoming division plant engineer in 1922, division construction superintendent 1925, division plant superintendent 1926, assistant general plant manager 1927, chief engineer Bronx-Westchester area 1927, general plant manager 1928, and vice-president and general manager, Long Island area, 1933. He became assistant vice-president in charge of staff engineering in 1933, and since April 1939 has been in charge of staff inventory and appraisal.

G. J. Fiedler (A'32) has been appointed associate professor of electrical engineering at Montana State College, Bozeman. He was formerly a member of the electrical-engineering department of Union College, Schenectady, N. Y. A native (1904) of Bushton, Kans., he received the degrees of bachelor of science in electrical engineering from Kansas State College (1926), master of science, University of Kansas (1932), electrical engineer, Kansas State College (1936). He was in the test department of General Electric Company at Pittsfield, Mass., and Schenectady, N. Y., 1926–28, and 1928–31 was associated with the Radio Corporation of America. He was laboratory assistant and later instructor at the University of Kansas, Lawrence, and director of the Albany, Schenectady, and Troy Collegiate Centers of the New York State Teachers' College, before going to Union in 1935.

E. W. Hamlin (A'35) has been appointed professor of electrical engineering at the University of Texas, Austin, where he will have charge of communication courses. Born July 21, 1905, at New York, N. Y., he received from Union College the degrees of bachelor of science, 1926; master of science, 1928; doctor of philosophy in electrical engineering, 1932. After spending the summer of 1926 in the test department of General Electric Company, Schenectady, N. Y., he became an instructor in electrical engineering at Union, at the same time carrying on graduate study. In 1935 he went to the University of Kansas, Lawrence, as assistant professor of electrical engineering, becoming associate professor in 1937. He is a member of the Society for Promotion of Engineering Education, Sigma Xi, and Eta Kappa Nu.

A. P. Gompf (A'27) has been appointed chief engineer, Chesapeake and Potomac Telephone Company of Virginia, Richmond. Born August 28, 1892, at Howardville, Md., he was graduated from Baltimore Polytechnic Institute and received the degree of bachelor of science in education from Columbia University. He was employed as an electrical draftsman by the Bethlehem Steel Company, Sparrow's Point, Md., in 1917, then went into military service, and 1919–20 served as apprentice instructor in the electrical and mechanical divisions, Panama Canal. He went with the Chesapeake and Potomac Company, Washington, D. C., in 1920 as an engineering assistant, becoming inventory and costs engineer of

the companies in 1927, and staff engineer, department of operation, in 1929, which position he held until his present appointment.

F. E. Brooks (A'38) has been appointed chief engineer of the Bronx-Westchester area, New York Telephone Company, New York, N. Y. He was born January 27, 1890, at Kansas City, Mo., and received the degrees of bachelor of science (1912) and electrical engineer (1921) from the Case School of Applied Science. He entered the engineering department of the New York Telephone Company in 1912 and except for military service 1917–19, has been with the company continuously. He was appointed engineer of plant extension, Bronx-Westchester area, in 1927, and in 1935 was given the same position in the Manhattan area, his duties being extended in 1937 to include electrical-engineering supervision of transmission design and maintenance. He is a member of Eta Kappa Nu.

B. W. Creim (A'20, F'31) has been appointed principal engineer in charge of the project construction section, engineering division, Bonneville Dam project, Portland, Ore. For the past three years he has been principal engineer for the Rural Electrification Administration, Washington, D. C., having charge of design and construction of rural systems in the western states. He was electrical engineer for the City of Los Angeles (Calif.) Bureau of Power and Light 1919–27 and chief electrical engineer for the Modesto (Calif.) Irrigation District from 1927 until 1936.

W. V. B. Van Dyck (A'01, M'31) assistant to the president, International General Electric Company, Schenectady, N. Y., has been awarded the Order of the Southern Cross by the government of Brazil, in recognition of his services in promoting good will between Brazil and the United States. Mr. Van Dyck was associated with General Electric in Rio de Janeiro, Brazil, from 1911 through 1926, as special representative in Brazil, managing director of General Electric of Brazil, and president of General Electric of South America. He returned to the United States in 1927 to become manager of the Schenectady office of International General Electric.

F. J. Leerburger (A'28, M'35) formerly senior assistant engineer with Maurice R. Scharff, consulting engineer, New York, N. Y., has been appointed principal valuation engineer for the New York State Public Service Commission. Mr. Leerburger, who holds the degrees of bachelor of arts, bachelor of science, and electrical engineer from Columbia University, was an engineer for the Duquesne Light Company, Pittsburgh, Pa., and the Foxboro Company, New York, N. Y., before joining the Scharff staff in 1932.

C. H. Buchanan (A'37) formerly design engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed instructor in electrical engineering, Iowa State College, Ames. He had been with Westinghouse since 1936, except for a leave of absence in 1937 during which he taught in the electrical-engineering department of Carnegie Institute of Technology, Pittsburgh.

W. F. Daly (A'20) has been placed in charge of the St. Louis (Mo.) district office of Allis-Chalmers Manufacturing Company. He had been connected with the Chicago office of the company since 1924, and before that time was with the Crocker-Wheeler Company in Chicago, Ill., and Ampere, N. J.

Daniel Silverman (A'33) geophysicist, Tulsa, Okla., has for some time been a member of the staff of the laboratory of the Western Geophysical Company and the Stanolind Oil and Gas Company, Tulsa, in charge of design, construction, test, and servicing of all geophysical instruments.

B. J. Rowan (A'28) has been appointed assistant to the manager of the publicity department, General Electric Company, Schenectady, N. Y., in charge of the administrative and production division. Since 1930 he had been district manager of the publicity department in New York, N. Y.

Frederic Attwood (M'27) vice-president, Ohio Brass Company, New York, N. Y., has been made a chevalier of the Legion of Honor of France, in recognition of military services and his activities in the International Conference on High-Voltage Electrical Systems (CIGRÉ), in which he is president of the American delegation and a vice-president of the Conference.

F. A. Farou (A'21, M'27) has been appointed assistant manager of the industrial department, New York district, General Electric Company. He was formerly manager of the New Haven, Conn., office of the company, with which he has been associated since 1916.

K. T. Compton (F'31) president of Massachusetts Institute of Technology, Cambridge, has been appointed chairman of a committee named by the National Association of Manufacturers to select outstanding inventors to be honored as "Modern Pioneers."

W. F. Nimmo (A'30, M'35) general engineering department, Virginia Electric Power Company, Richmond, has been appointed chairman of the Edison Electric Institute's committee on transmission and distribution for 1939–40.

J. H. Smith (A'32) has joined the teaching staff of the electrical-engineering department, University of Illinois, Urbana. He was formerly professor of electrical engineering at Detroit Institute of Technology, Detroit, Mich.

L. V. Banta (A'34) formerly sales service engineer, Edison Storage Battery Supply Company, San Francisco, Calif., has been transferred to the sales engineering department, storage battery division, Thomas A. Edison, Inc., West Orange, N. J.

C. R. Smith (A'39) formerly a student engineer with the General Electric Company, Schenectady, N. Y., has been appointed instructor at the Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia.

D. S. Smith (A'33) formerly power apparatus engineer, Northern Electric Company, Ltd., Montreal, Que., Can., has joined the staff of the National Research Council, department of physics and electrical engineering, at Ottawa, Can.

E. E. Powell (A'37) has been appointed district engineer of Southwestern Bell Telephone Company, with headquarters at St. Joseph, Mo. He was formerly exchange inventory supervisor, Wichita, Kans., and chairman of the AIEE Wichita Section.

R. H. Anthony (A'17) sales engineer, Boston, Mass., has been appointed New England correspondent of Sweitzer and Conrad, Inc. He also represents the G. and W. Electric Specialty Company and the Electroline Company.

H. C. Ellmaker (A'35) has become assistant electrical engineer, United States Engineer's Office, Los Angeles, Calif. He was formerly recording engineer with the engineering firm of Batsley and Phillips, Los Angeles.

W. E. Haywood (M'36) formerly district plant superintendent, American Telephone and Telegraph Company, Dallas, Tex., has been transferred by the company to New York, N. Y., as engineer.

R. W. Ahlquist (A'35) formerly assistant professor of electrical engineering, University of Pittsburgh, Pittsburgh, Pa., has been appointed assistant professor of electrical engineering, Iowa State College, Ames.

F. A. Engel, Jr. (A'39) has been employed by the Speer Carbon Company Laboratories, St. Mary's, Pa.

F. E. BROOKS

A. P. GOMPF

Backrack

E. J. O'CONNELL

G. F. Tracy (A'26) who has been associate professor of electrical engineering at the University of Toronto, Toronto, Can., has returned to his former position as associate professor of electrical engineering, University of Wisconsin, Madison.

H. L. Wallau (A'00, F'13) electrical engineer, Cleveland Electric Illuminating Company, Cleveland, Ohio, has been appointed chairman of the Edison Electric Institute's committee on electrical equipment for the year 1939–40.

E. F. Weaver (A'26) formerly superintendent, Lehigh division, Pennsylvania Power and Light Company, Allentown, Pa., has been appointed superintendent of transmission of the company, with headquarters at Hazelton, Pa.

G. M. S. Stein (M'38) formerly electrical engineer, Federal Machine and Welder Company, Warren, Ohio, has entered the transformer engineering department of Westinghouse Electric and Manufacturing Company, Sharon, Pa.

David Younger (A'37) who has been district plant engineer, American Telephone and Telegraph Company, Buffalo, N. Y., has been transferred by the company to the office of the general plant superintendent, New York, N. Y.

E. W. Kimbark (A'27, M'35) has been appointed assistant professor of electrical engineering, Northwestern University, Evanston, Ill. He formerly held the same position at Brooklyn Polytechnic Institute, Brooklyn, N. Y.

J. R. Fritz (A'38) former assistant district superintendent, New Jersey Power and Light Company, Flemington, has become an instructor in electricity at the Wyomissing Polytechnic Institute, Wyomissing, Pa.

R. E. Ehrenfeld (M'24) formerly small-motor designer, Westinghouse Electric and Manufacturing Company, Lima, Ohio, has been employed as electrical engineer by the Apex Electrical and Manufacturing Company, Cleveland, Ohio.

Alfred Skrobisch (A'36) formerly application engineer, Tung-Sol Lamp Works, Inc., Newark, N. J., has been employed in the control engineering department, Curtiss Propeller division, Clifton, N. J., of the Curtiss-Wright Corporation.

S. O. Evans (A'33) formerly engineer, General Electric Company, Pittsfield, Mass., has been appointed assistant professor of electrical engineering, Ohio State University, Columbus.

J. T. Henderson (A'32) formerly electrical engineer, General Electric Company, Lynn, Mass., has been employed as electrical-engineering draftsman, Central New York Power Company, Syracuse, N. Y.

C. F. Kettering (A'04, F'14) vice-president in charge of research, General Motors Corporation, Dayton, Ohio, received the honorary degree of doctor of science from Dartmouth College in June 1939.

W. R. Smith (M'18, F'30) safety engineer, Public Service Electric and Gas Company, Newark, N. J., has been appointed chairman of the committee on accident prevention of the Edison Electric Institute for 1939–40.

T. J. Woth (A'33) engineer, Westinghouse Electric and Manufacturing Company, has been transferred from the Buffalo, N. Y., office of the company to the Atlanta, Ga., office.

L. E. Cook (A'25, M'35) formerly supervisor of distribution, Texas Power and Light Company, Dallas, has been employed as electrical engineer by Ebasco Services, Inc., New York, N. Y.

J. M. Noy (A'37) has been employed as research chemist and metallurgist by the Foote Mineral Company, Inc., Philadelphia, Pa.

Obituary

Arnold Honegger (A'15, M'28) vice-president, Business Research Corporation, Chicago, Ill., died June 20, 1939. He was born November 1, 1879, at St. Gallen, Switzerland, and was graduated from the Institute for Electrical and Mechanical Engineers, Mitweida, Saxony, Germany, in 1902. He was employed for a year by the General Electric Company, Schenectady, N. Y., on designing and drafting transformers and switchboards, and from 1903 to 1907 was engaged in design and construction for the St. Louis and Suburban Railway, St. Louis, Mo.; the National Construction Company, St. Louis; the Chicago City Railway Company, Chicago, Ill.; and the Electrical Installation Company, Chicago. He was employed from 1907 to 1911 by the Falkenau Electrical Construction Company of Chicago, and in 1911 entered the employ of the International Harvester Company, by which organization he was sent to Russia, where he represented that company and others until 1915. He was engaged in construction and engineering for A. M. Hewes and Company, Chicago; Nebraska Electric Company, Omaha; Winslow Brothers Company, Chicago; and Sessions Engineering Company, Chicago, until 1920, when he became assistant director of the Business Research Corporation. He continued with that organization until his death.

Charles William Godson Little (A'96) retired chief engineer, British Electrical Federation, London, Eng., died recently, according to information received at Institute headquarters. He was born at Heckington, Lincolnshire, Eng., in 1866, and was educated at Finsbury Technical College. In 1889 he became associated with the Thomson-Houston International Electric Company, Boston, Mass., was transferred in 1891 to the French Thomson-Houston Company, Paris, and in 1893 joined the newly formed British Thomson-Houston Company, Ltd., later becoming chief of the construction department. In 1899 he joined the British Electric Traction Company as chief executive electrical engineer, being connected with lighting, power, and traction undertakings in England and also in New Zealand and India. He later became associated with the British Electrical Federation, and in that connection was sent to Brazil, Argentine, and Russia. He retired as chief engineer in 1930. He was a member of The Institution of Electrical Engineers of Great Britain.

Charles W. Davis (M'29) president and general manager, Dallas Power and Light Company, Dallas, Tex., died September 16, 1939. He was born at Sandusky, Ohio, November 10, 1874, and attended Ohio State University. During the years 1894 to 1900 he was associated with the Maryland Electric Company, Brush Electric Company, and Westinghouse Electric Company, all of Baltimore, Md., the Fort Wayne, Ind., Electric Company, and the Warren Electric Company, Sandusky. During the next two years he was engaged in the construction and operation of lighting plants in Texas, and from 1902 to 1904 sold equipment for the Southwestern Electric Engineering and Construction Company, Dallas. He became district manager of the Westinghouse Electric and Manufacturing Company in Dallas in 1904, continuing in that position until 1919 when he became vice-president and general manager of the Dallas Power and Light Company. He was made president of the company in 1930.

Leo Dorsey Firman (A'06, M'13) consulting engineer, Leesburg, N. J., died recently, according to information just received at Institute headquarters. He was born January 2, 1864, at Carversville, Pa. He began his electrical career in 1881 as telegraph operator, working as operator and assistant wire chief for various companies. In 1887 he was employed by the Western Union Telegraph Company, Philadelphia, Pa., as operator, later becoming wire chief. He was employed in 1895 as an inspector by the City of Philadelphia Electrical Bureau, in 1905 became assistant inspector of electric lighting, and in 1908 assistant chief of the Bureau. In 1916 he went with Stockwell, Wilson, and Linvill, Philadelphia, later becoming appraisal engineer for the firm, and subsequently entered independent practice as a consulting electrical engineer.

Roy Bingham Ashbrook (A'20, M'30) communication engineer, Southern California Edison Company, Ltd., Los Angeles, Calif., died August 15, 1939. He was born July 28, 1890, at Kansas City, Mo., and educated there. From 1906 through 1909, he was employed by Western Electric Company and the Missouri and Kansas Telephone Company, in Kansas City. He was with the Pacific Telephone and Telegraph Company, Los Angeles, Calif., 1910–12, and in 1913 entered the employ of Southern California Edison. After four years with the test department he was made responsible for the company's communication services. He supervised the growth of the communications system, designing much equipment for special purposes. He was a member of the Institute of Radio Engineers.

Richard Henry Silbert (A'17, M'27) industrial service representative, Philadelphia Electric Company, Philadelphia, Pa., died recently, according to information received at Institute headquarters. He was born at Philadelphia, Pa., July 28, 1880. In 1900 he was employed by the Bell Telephone Company of Philadelphia, and in 1902 by Western Electric Company, installing telephone facilities in Philadelphia and adjacent areas. He was employed by the Philadelphia Electric Company in 1904, spent 1905–06 with the West Jersey and Seashore Railroad, and returned to Philadelphia Electric in 1906, continuing with the company until his death. He was successively inspector, special inspector, assistant superintendent of inspection, and industrial service representative.

William Trudgian (A'27) special representative, Westinghouse Electric and Manufacturing Company, Denver, Colo., died September 19, 1939, at Craig, Colo. He was born in Galena, Ill., December 22, 1881, and received the degree of bachelor of science in electrical engineering from the University of Colorado in 1907. He entered the employ of the Westinghouse company the same year, and except for one year, 1918–19, spent as an inspector for the United States Government, continued with the company the rest of his life. He was manager of the district including Colorado, Wyoming, and New Mexico, 1930–35, and since 1935 had been special representative in the same district.

Sanford Bennett Waring (A'35) assistant electrical-engineering draftsman, Signal Service at Large, United States War Department, Atlanta, Ga., died recently, according to information received at Institute headquarters. He was born at Sandwich, Mass., October 30, 1912, and received the degree of bachelor of science in electrical engineering from the University of Florida in 1934. He was employed as a draftsman by the Florida State Road Department, Ocala; in the City Engineer's office, Gainesville, Fla., on a Federal public buildings survey in Gainesville, and later as office engineer of the City Engineer's office, before taking the Signal Service position.

Membership

Recommended for Transfer

The board of examiners, at its meeting on October 19, 1939, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Booth, Jesse James, assistant superintendent of maintenance, Carnegie-Illinois Steel Corporation, Duquesne, Pa.
Green, W. W., technical representative in Europe, American Telephone and Telegraph Co., and Bell Telephone Laboratories, Inc., London, Eng.
Hill, C. F., research physicist, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Scott, R. C., vice-president and chief engineer, Mutual Boiler Insurance Company of Boston, Mass.

4 to Grade of Fellow

To Grade of Member

Cooper, J. B., electrical engineer, General Electric Company, Pittsfield, Mass.
Dickinson, H. F., electrical engineer, Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.
Hoover, P. L., head of electrical engineering department, Case School of Applied Science, Cleveland, Ohio
Keen, A. H., local office manager, General Electric Company, Fort Worth, Tex.
Petrie, A. E., power development engineer, Bell Telephone Laboratories, Inc., New York, N. Y.
Sine, R. R., electrical engineer, Rome Cable Corporation, Rome, N. Y.
Strang, H. E., managing engineer, large oil circuit breaker division, General Electric Company, Philadelphia, Pa.

7 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before November 30, 1939, or January 31, 1940, if the applicant resides outside of the United States or Canada:

United States and Canada

1. NORTH EASTERN

Arnold, R. E. (Member), General Electric Company, West Lynn, Mass.
Paul, J. E., Union College, Schenectady, N. Y.
Walter, B. M., General Electric Company, Pittsfield, Mass.

2. MIDDLE EASTERN

Angier, M. S., Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.
Campbell, D. A., Jr., Pennsylvania Power and Light Company, Allentown, Pa.
Cottle, C. H., The Scranton Electric Company, Scranton, Pa.
Davis, H. L., Consolidated Gas Electric Light and Power Company, Baltimore, Md.
Johnson, C. H., Line Material Company, Allentown, Pa.
Kiss, M. A., Hickok Electrical Instrument Company, Cleveland, Ohio.
Mancill, R. D., I-T-E Circuit Breaker Company, Philadelphia, Pa.
Northup, Y. E., The Scranton Electric Company, Scranton, Pa.
Park, R. B., The Scranton Electric Company, Scranton, Pa.
Poole, L. C., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Sweets, J. E., American Telephone and Telegraph Company, Cleveland, Ohio.
Thompson, H. B. (Member), Westinghouse Electric and Manufacturing Company, Washington, D. C.
Waxman, A. S., Bethlehem Steel Company, Sparrows Point, Md.

3. NEW YORK CITY

Baker, R. (Member), Long Island Lighting Company, Mineola, N. Y.
Kaiser, E. T., Prudential Insurance Company of America, Newark, N. J.
LaVino, R. B., Interborough Rapid Transit Company, New York, N. Y.
Lichty, H. F., Rifer Electric, Inc., Union City, N. J.
Lindsay, N. W., Westchester Lighting Company, Mount Vernon, N. Y.
Petersen, A. H. (Member), Columbia Broadcasting System, New York, N. Y.
Scott, C. F., Western Electric Company, Inc., Kearny, N. J.
Thayer, P. H., Jr., Bell Telephone Laboratories, Inc., New York, N. Y.
Van Tassell, W. H., Westchester Lighting Company, Mount Vernon, N. Y.

4. SOUTHERN

Carpenter, R. C., Electrical Engineering and Repair Company, Atlanta, Ga.
Sittloh, C. F., Alabama Power Company, Birmingham.

5. GREAT LAKES

Curtis, F., American Brass Company, Detroit, Mich.
Goodell, P. H. (Member), C. M. Hall Lamp Company, Detroit, Mich.
Newman, M., University of Minnesota, Minneapolis.
Oerman, H. W., Public Service Company of Northern Illinois, Chicago, Ill.
Rupprecht, W. J. L., The Dow Chemical Company, Midland, Mich.

7. SOUTH WEST

Barron, J. P., Dallas Power and Light Company, Dallas, Tex.
Baumann, L., Square D Company, Houston, Tex.
Butler, J. J., Westinghouse Electric and Manufacturing Company, St. Louis, Mo.
Hull, S. B., Southwestern Bell Telephone Company, Dallas, Tex.
McLeod, L. W., Westinghouse Electric and Manufacturing Company, St. Louis, Mo.
Nielsen, L., Southwestern Bell Telephone Company, Oklahoma City, Okla.
Price, E. R., Westinghouse Electric and Manufacturing Company, Dallas, Tex.
Schultz, L. H., Southwestern Bell Telephone Company, St. Louis, Mo.
Wise, E. C., General Electric Company, El Paso, Tex.

8. PACIFIC

Barneby, G. L., Southern California Edison Company, Wilmington, Calif.
Bustard, W. B., Westinghouse Electric and Manufacturing Company, Phoenix, Ariz.
Craig, F. D., 1021 Mariposa Avenue, Berkeley, Calif.
Harrison, R. C. (Member), Central Arizona Light and Power Company, Phoenix, Ariz.
Hickey, F. W., Jr., Public Works Administration, San Francisco, Calif.
Jones, W. W. (Member), Fog Nozzle Company, Los Angeles, Calif.

9. NORTH WEST

Christensen, L. J., West High School, Salt Lake City, Utah.

10. CANADA

Gray, J. B., Georgetown Hydro Electric Power Commission, Georgetown, Ont.
Otis, A. M., Hamilton Hydro Electric System, Hamilton, Ont.
Stockman, E. O., C. A. Parsons and Company, Ltd., Toronto, Ont.

Total, United States and Canada, 51

Elsewhere

Angus, J. H. (Member), Electricity Department, Port Elizabeth, South Africa.
Shilcock, A. E. (Member), Cable and Wireless (W. I.), Ltd., San Juan, Puerto Rico.

Total, elsewhere, 2

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Crawford, Wade P., Box 364, Coeur D'Alene, Idaho.
Doherty, Joseph F., 901 Hill St., Wilkinsburg, Pa.
Evans, David T., Box 194, Anyox, B. C., Can.
Hall, John R., c/o Patrick Tyrrell Drilling Co., Cotton Exchange Bldg., Houston, Texas.
Holifield, Ray, 5116 Milam St., Dallas, Texas.
Keiser, M., 1841 Broadway, New York, N. Y.
Lovett, Morris, Diehl Manufacturing Company, Elizabethport, N. J.
McCarthy, C. C., c/o Westinghouse Electric and Manufacturing Co., 814 Ellicott Square, Buffalo, N. Y.
O'Fiel, J. C. Dudley, Jr., 1214 Chartres St., Houston, Texas.
Pyne, Arnold N., 627 Third St., Niagara Falls, N. Y.
Sanchez, Hector M., 12 De Diegos Ave., Santurce, Puerto Rico.
Shimp, Robert P., 3749 N. Gratz St., Pittsburgh, Pa.
Taylor, Richard V., Hotel Wood, Jefferson & Clinton St., Syracuse, N. Y.
Teuscher, F. P., Apto. 1003, Mexico, Mex.

14 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Electrical engineers may be interested in the following new books, which are among those recently received at the Engineering Societies Library, New York, N. Y. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries information for which is taken from the preface of the book in question.

PETROLEUM PRODUCTION ENGINEERING, OIL FIELD EXPLOITATION. By L. C. Urge. Second edition. New York and London. McGraw-Hill Book Company, 1939. 756 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Revised and extended edition of the part of "Petroleum Production Engineering" that discusses oil-field exploitation. Affords a survey of the technology of oil production, covering methods and equipment and the physical principles, that control the recovery of petroleum from its reservoir rocks. Each chapter has a selected list of references.

ATOMS IN ACTION, THE WORLD OF CREATIVE PHYSICS. By G. R. Harrison. New York, William Morrow and Company, 1939. 370 pages, illustrated, 9 by 6 inches, cloth, $3.50. A presentation of what modern physicists think and do, and of some applications of their work in daily life.

ENGINEERING PHYSICAL METALLURGY. By R. H. Heyer. New York, D. Van Nostrand Company, 1939. 549 pages, illustrated, 9 by 6 inches, cloth, $4.50. Intended for those making their first acquaintance with engineering metals and alloys. A wide range of materials is discussed, including pure metals and alloys, processes of hot and cold reduction, heat treatment, welding machining, and so forth. Each chapter has a bibliography.

MATHEMATICS OF STATISTICS, Parts 1 and 2. By J. F. Kenney. New York, D. Van Nostrand Company, 1939. Part 1, 248 pages; Part 2, 202 pages, diagrams, etc., 9 by 6 inches, cloth, $4.00. An elementary textbook that calls for no mathematics beyond the ordinary freshman course in college algebra, this work introduces the fundamental principles and concepts that underlie the applications of statistics in various fields.

A MUSICAL SLIDE RULE. By L. S. Lloyd. London and New York, Oxford University Press, 1938. 25 pages, diagrams, tables, 9 by 6 inches, paper, $0.75. This booklet is intended as an introduction to the study of the musical scale employed by composers. Describes the differences between the scale of the tuned keyboard instrument and that played on a stringed instrument or sung. The reasons for the discrepancies are explained and directions are given for determining these discrepancies by means of a simple slide rule which accompanies the pamphlet.

PHYSICAL AND DYNAMICAL METEOROLOGY. By D. Brunt. Second edition. Cambridge, England, University Press; New York, The Macmillan Company, 1939. 428 pages, diagrams, etc., 10 by 7 inches, cloth, $6.75. Aims to provide English-speaking students with a textbook, suitable for postgraduate study, which will represent our present knowledge of theoretical meteorology as completely as possible. The new edition has been extended and in part rearranged.

ALTERNATING CURRENTS. By C. E. Magnusson. Fifth edition. New York and London, McGraw-Hill Book Company, 1939. 719 pages, illustrated, 9 by 6 inches, cloth, $5.00. This textbook presents the basic principles of alternating currents and their application to electric-power engineering. Revised to represent current conditions.

THE DISEASES OF ELECTRICAL MACHINERY. By G. W. Stubbings. New York, Chemical Publishing Company, 1939. 219 pages, diagrams, 8 by 5 inches, cloth, $3.00. Manual for power-plant engineers and electricians. The defects that arise in the operation of electrical machinery are discussed, their underlying causes explained, and practical directions given for their location and rectification.

VAPOR CHARTS AND SPECIAL TABLES FOR TURBINE CALCULATIONS. By F. O. Ellenwood and C. O. Mackey. New York, John Wiley and Sons, 1939. 43 pages, charts, tables, 11 by 8 inches, cloth, $2.50. These vapor charts replace the "steam charts" published by Mr. Ellenwood in 1914. The book form of chart is retained, but the tables for steam have been greatly extended and improved, and charts showing the thermodynamic properties of water, ammonia, dichlorodifluoromethane (freon-12), and mixtures of air and water vapor have been added.

ELECTRICITY TODAY. (The Pageant of Progress.) By T. B. Vinycomb. New York and London, Oxford University Press, 1939. 192 pages, illustrated, 9 by 6 inches, cloth, $1.75. Gives nontechnical readers an account of the way electricity is produced and distributed and of its uses in daily life. Heating, lighting, and methods of communication are described in terms of current practice.

ATM (ARCHIV FÜR TECHNISCHES MESSEN). Lieferungen 94–96, April 1–June 1939. Munich and Berlin, R. Oldenbourg, 1939. Illustrated, 12 by 8 inches, paper, 1.50 rm. each. Three numbers of a monthly publication containing classified articles upon various types of apparatus and methods for technical measurements; also some descriptions of specific instruments manufactured by German companies.

Great Britain, Department of Scientific and Industrial Research. REPORT 1937–38. London, His Majesty's Stationery Office, 1939. 203 pages, charts, 10 by 6 inches, paper, 3s. (obtainable from British Library of Information, 50 Rockefeller Plaza, New York, $0.90). Reviews the work of the various committees and associations and so affords a general survey of the scientific and industrial research work carried out in Great Britain during the year. Appendices give directories of the departments and associations and their officers, lists of the publications of the year, expenditures, and so on.

HEATING AND AIR CONDITIONING. By J. R. Allen and J. H. Walker. Fifth edition. New York and London, McGraw-Hill Book Company, 1939. 1005 pages, illustrated, 9 by 6 inches, cloth, $4.50. Presents the theory underlying heating and air conditioning, together with practical information upon design and equipment. Adapted for use in engineering schools or for home study. Revised and enlarged edition.

INDUSTRIAL ELECTRICITY, Part 1. By C. L. Dawes. Second edition. New York and London, McGraw-Hill Book Company, 1939. 387 pages, illustrated, 9 by 6 inches, cloth, $2.20. For use in technical high schools and other schools not of collegiate grade where elementary electrical engineering is taught. The fundamentals of electrical engineering are presented and their industrial applications discussed. Revised to accord with current practice.

PATENTS AND THE PUBLIC INTEREST. By H. A. Toulmin. New York and London, Harper Brothers, 1939. 205 pages, illustrated, 9 by 6 inches, cloth, $2.50. Surveys our patent system critically and suggests lines of improvement. Discusses the reasons for the system, the relation between patents and such public problems as patent pools, unemployment, and patent suppression, and analyzes various proposals for reform. The final section describes the results of various modern inventions.

RECLAMATION 1902–1938. A SUPPLEMENTAL BIBLIOGRAPHY. (Regional Checklist No. 6, May 1939.) Compiled by J. J. Gaul at the Bibliographical Center for Research, Rocky Mountain Region, the Denver Public Library, Denver, Colo., 1939. 98 pages, manifold copy, 11 by 9 inches, cardboard, $1.00. Includes references on land reclamation not included in the three best known bibliographies devoted to that subject. About 1,500 references, arranged by author, with indexes by states, projects, and dams.

STEAM, AIR, AND GAS POWER. By W. H. Severns and H. E. Degler. Third edition. New York, John Wiley and Sons, 1939. 511 pages, illustrated, 9 by 6 inches, cloth, $4.00. This textbook presents "illustrations, descriptions, and underlying theory of construction, application, and performance of modern heat power plants and their correlated equipment." Numerous changes in this edition reflect recent progress.

TERRESTRIAL MAGNETISM AND ELECTRICITY. (Physics of the Earth, VIII) edited by J. A. Fleming. New York and London, McGraw-Hill Book Company, 1939. 794 pages, illustrated, 10 by 7 inches, cloth, $8.00. Eighth of a series of monographs upon the physics of the earth prepared by specialists under the direction of various committees of the National Research Council. This volume reviews our knowledge of the earth's magnetic and electrical phenomena. Magnetic surveys and instruments, magnetic prospecting, atmospheric electricity, the outer atmosphere, the aurora polaris, and thunderclouds are among the subjects presented. Bibliography of over 1,500 items.

WAVE-LENGTH TABLES With Intensities in Arc, Spark, or Discharge Tube of More Than 100,000 Spectrum Lines Most Strongly Emitted by the Atomic Elements Under Normal Conditions of Excitation Between 10,000 A. and 2,000 A., Arranged in Order of Decreasing Wave Lengths. Measured and compiled under the direction of G. R. Harrison by staff members of the spectroscopy laboratory of the Massachusetts Institute of Technology, assisted by the Works Progress Administration. Cambridge, Mass., Technology Press; New York, John Wiley and Sons, 1939. 429 pages, illustrated, 11 by 8 inches, cloth, $15.00. The most extensive catalog that has yet appeared; this volume, valuable to all, is sufficiently described by its title.

WINTER AIR CONDITIONING; FORCED WARM-AIR HEATING. Edited by S. Konzo. Columbus, Ohio, National Warm-Air-Heating and Air-Conditioning Association, 1939. 532 pages, illustrated, 9 by 6 inches, cloth, $3.00. Based largely upon the research work in forced-air heating conducted in the warm-air-heating research residence at the University of Illinois since 1932. From this and supplementary data a comprehensive survey of the present status of the design, installation, and operation of the forced-air heating plant is gained. Extensive calculations, both theoretical and actual, are included for all phases of the subject.

PHYSIK. By P. Wessel and V. R. von Paar. Munich, Ernst Reinhardt, 1938. 514 pages, diagrams, etc., 8 by 5 inches, leather, 4.90 rm. This college textbook, which covers the customary topics included in physics courses, uses many illustrations and heavy type to explain certain equations to clarify and emphasize important points. Contains a review section, test questions, with references to the appropriate sections of the text, and a detailed index.

SCHWEISSKONSTRUKTIONEN. (Einzelkonstruktionen aus dem Maschinenbau, Heft 9.) By R. Häuchen. Berlin, Julius Springer, 1939. 123 pages, illustrated, 11 by 8 inches, paper, 18.60 rm. The fundamentals of welding processes are covered in the first part of this work, including a discussion of materials and their weldability, the preparation of parts to be welded, seam formation, and graphic symbols representing various welds. The second and third parts consider calculations of welded joints for strength and safety, and the form of parts to be welded. In the final section actual jobs of welded construction are described and illustrated.

GREAT ENGINEERS. By C. Matschoss, translated by H. S. Hatfield. London, G. Bell and Sons, 1939. 381 pages, illustrated, 8 by 6 inches, cloth, 12s. 6d. This translation from the German contains short biographies of great engineers from antiquity to the 20th century. Emphasizes the human attributes of the men, their personalities, vicissitudes, and ultimate success.

COMPLEX VARIABLE AND OPERATIONAL CALCULUS WITH TECHNICAL APPLICATIONS. By N. W. McLachlan. Cambridge, England, University Press; New York, The Macmillan Company, 1939. 355 pages, diagrams, etc., 9 by 6 inches, cloth, $6.50. The author has based his theory of operational procedure on the Mellin inversion theorem, a combination of complex integration and the Laplace integral. The main treatment appears in part II. Part I contains an exposition of the theory of the complex variable, covering the technique of complex integration. In part III the application of the method to problems in various branches of technology is illustrated. Includes examples to be worked out, specific derivations, and list of references.

Engineering Societies Library

39 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Transactions

Papers and Discussions Comprising Pages 563–610 of the 1939 Volume

Voltage Control of Mercury-Arc Rectifiers

G. R. McDONALD
ASSOCIATE AIEE

THE mercury-arc rectifier competes with the older well-established types of apparatus, the synchronous converter and motor generator set. Both of these types of apparatus are flexible in application as they may be adjusted through a range of different output characteristics and in the case of the booster-type converter and motor generator set, considerable range in voltage control is possible. In order to take full advantage of the desirable features of the mercury-arc rectifier, its output voltage should duplicate that of its rivals.

The output of a rectifier and its associated transformer without any special means of modifying or regulating the voltage is similar to that of a shunt-connected generator in that an increase in load causes a reduction in the direct voltage. The characteristic is a straight line from light load to the rated capacity of the equipment. The slope of this characteristic is dependent upon the type of transformer connections used, the reactance and resistance of the transformer and supply system, and the arc-drop characteristic of the rectifier.[1]

The importance of the flat-compound characteristic has long been recognized particularly in the railway field. One of the earliest attempts at modifying the voltage output of a rectifier consisted of a scheme to produce the flat compound characteristic.[2] In figure 1 a commonly used rectifier circuit is shown, with the exception that the interphase transformer is provided with a saturating winding. If this transformer and its winding were short-circuited by the dotted connections x and y, a six-phase diametric connection would be obtained having an output characteristic as shown by AB.

If the dotted connection x is now removed the interphase transformer is placed in operation and six-phase operation is still obtained but the resulting connection is known as double three phase, the two wyes being forced to operate in multiple by the interphase transformer. The output of the rectifier is still six phase as the two three-phase systems are displaced from each other by 60 degrees. This characteristic is shown by ACD.

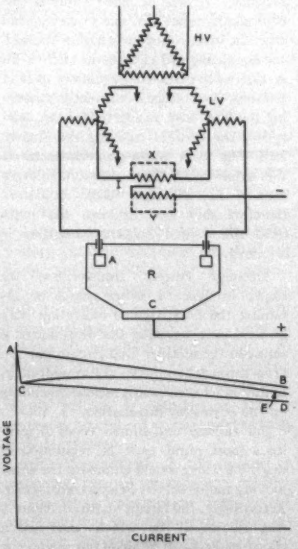


Figure 1

HV—Transformer high-voltage winding
LV—Transformer low-voltage winding
I—Interphase transformer
R—Rectifier
A—Main anode
C—Cathode

It is apparent that any gradual means of making the interphase transformers ineffective with an increase in load would produce a characteristic similar to ACE. If the short circuit across the interphase saturating winding is now removed and the interphase transformer is made ineffective by saturation in proportion to the d-c output, the desired compound characteristic would be obtained.

An equipment of this kind was described in the TRANSACTIONS of the AIEE. The actual characteristic obtained was shown in the article.[3]

The circuit for compounding described above has the disadvantage of employing saturation of the magnetic circuits, making it difficult to obtain a smooth curve of the desired shape. In addition it causes a poor power factor. To overcome these difficulties a more flexible scheme of compounding was developed as shown in figure 2. In this figure the interphase transformer has connected across it a circuit made up of a saturating reactor and capacitor. The capacitors used in this way advance the firing period of the rectifier anodes, thus compensating for the reactive part of the normal rectifier regulation. The point at which the capacitors have the maximum effectiveness is determined by the constants of the circuit. The advantages of this circuit are: increased flexibility in adjustment, better utilization of the main transformer windings, improvement in power factor, and decreased losses.

A simple way of changing a rectifier direct output voltage is to vary the alternating voltage applied to the rectifier. This can be accomplished by any of the commonly used methods for regulating or changing the voltage of an a-c circuit. In general, however, this type of voltage control is not suitable with rapidly fluctuating loads.

With progress in the art of rectifier design, control grids were introduced which were capable of modifying the starting point of the arc from the rectifier main anodes. By delaying the firing of the anodes, a reduction in the output voltage is possible. Voltage regulation by this means has been fully described in a number of articles.[4–7] This type of regulation is very flexible and any desired output voltage can be produced providing the desired voltage lies below the

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1. For all numbered references, see list at end of paper.

natural output characteristic of the rectifier.

This type of voltage regulation imposes some additional duty on the main anodes. It makes no change in the main transformer but does cause an increase in the size of the interphase transformer if used. One of the main objections to excessive use of voltage reduction by grid control is the distortion which it produces in the a-c power supply system and the d-c output of the rectifier.

In order to produce this type of regulation it is necessary to obtain the proper sequence in making the grids positive with respect to the voltage of the rectifier cathode. One of the simplest means of doing this is by a Selsyn phase-shifting transformer as shown by figure 3.

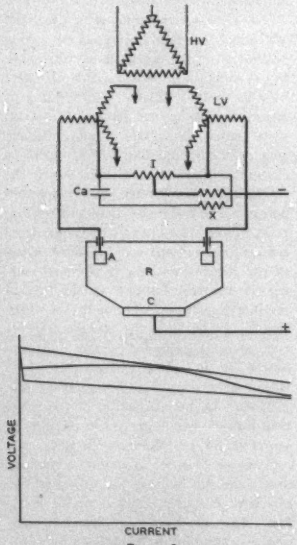

Figure 2

HV—Transformer high-voltage winding
LV—Transformer low-voltage winding
I—Interphase transformer
Ca—Capacitor
X—D-c saturating reactor
R—Rectifier
A—Anode
C—Cathode

The normal unregulated characteristic of the rectifier is shown by the curve *ABC*. When the Selsyn transformer is adjusted to retard the firing of the anodes and left in position, a characteristic curve parallel to the normal characteristic of the rectifier is obtained but at a lower voltage such as *ADE*. A number of equipments have been installed with control of this type so that the voltage of the rectifiers could be manually adjusted.

A simple modification of the scheme shown in figure 3 is the addition of a voltage regulator equipment and motor drive for the Selsyn transformer. With this equipment the regulator serves to maintain constant direct voltage. This type of regulation has been used for a number of equipments operating under steady load conditions where rapid control of the direct voltage is not necessary.

By means of a winding on the voltage regulator, carrying direct current in proportion to the rectifier output, the voltage can be made to rise or fall with an increase in d-c load as desired.

Load balance coils on the regulators will also balance the load quite accurately between two or more equipments. Figure 4 illustrates one method of obtaining a directional indication of the magnitude of the load being carried by a rectifier. The load indication is taken from a current transformer in the supply to the rectifier. It will be noted that if one equipment tends to carry more load than the other a current will flow through the equalizing coil circuits in such a direction as to cause the regulators to tend to boost the voltage of the rectifier carrying the least load and to reduce the voltage of the rectifier carrying the greater load. As both units are connected to the same bus, their output voltages cannot be different. The regulators therefore shift load between the units until the desired balance in output is obtained.

Although current transformers are shown in figure 4, other means of obtaining the load balance indication may be used such as using the drop across a shunt in the rectifier load circuit, the d-c drop through the interphase transformer, or any other convenient means depending on the particular installation.

For railway and similar types of service a more rapid type of regulation is desirable which would eliminate the slow-moving motor-driven Selsyn transformer. Accordingly, the circuit shown in figure 5 was developed in which the Selsyn transformer is still retained but merely for making the initial phase-angle adjustments. The necessary phase shifting of the grid voltage with respect to the voltage of the main anodes is obtained by applying a d-c bias to the neutral of the Selsyn transformer. The biasing voltage is obtained from a small d-c generator,

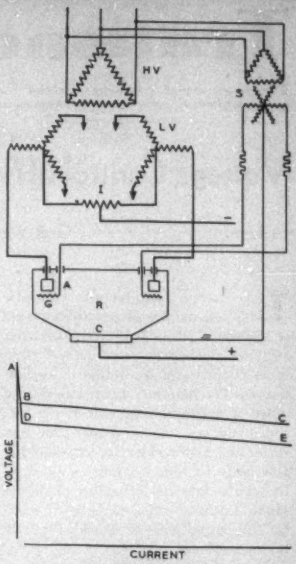

Figure 3

HV—Transformer high-voltage winding
LV—Transformer low-voltage winding
I—Interphase transformer
S—Selsyn phase-shifting transformer
R—Rectifier
A—Anode
G—Grid
C—Cathode

the output of which is controlled by the regulator. This does not produce any phase-angle shift of the a-c supply to the grids but by biasing the grid voltage there is, however, available a change in the time at which the grids go positive with respect to the cathode of approximately 90 degrees, although a much smaller shift is commonly used.

In figure 5 a biasing generator is connected between the cathode of the rectifier and the neutral of the six-phase grid transformer. This generator is provided with two separately excited shunt fields connected to oppose each other, one double the strength of the other. With this scheme of excitation the full range in voltage of the bias generator may be obtained in either direction. The output voltage of this generator is controlled by the regulator.

From the wave shapes shown in figure 5, keeping in mind that a rectifier anode cannot fire until its associated grid becomes positive with respect to the cathode, it will be noted that by means

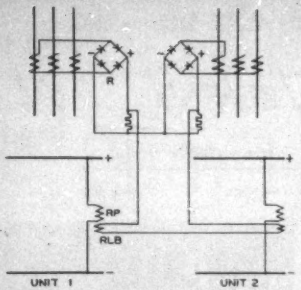

Figure 4

R—Copper-oxide rectifier
RP—Voltage regulator potential coil
RLB—Voltage regulator load balance coil

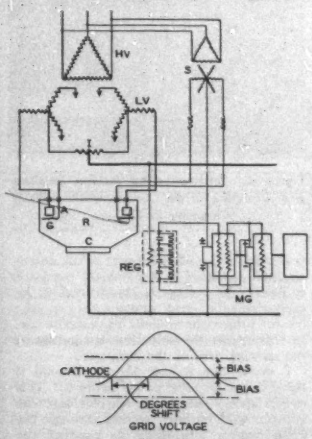

Figure 5

HV—Transformer high-voltage winding
LV—Transformer low-voltage winding
S—Selsyn transformer
R—Rectifier
A—Anode
G—Grid
C—Cathode
REG—Voltage regulator
MG—Grid-bias motor generator set

of this d-c bias there is a range of 90 degrees through which the firing of the main anode may be controlled. This gives a range from the normal unregulated voltage of the rectifier to approximately zero voltage if the load is sufficiently inductive to maintain the flow of current. This extreme range is not normally used but illustrates the flexibility of this type of control.

With this method a regulator can hold constant direct voltage or can be under- or overcompounded. The regulators can be equipped with load balance coils for balancing load between units.

The response of the rectifier to a change in grid voltage is practically instantaneous. This type of regulation is therefore very fast, the only delay being in the response of the regulator itself and in the ability of the separately-excited bias generator to change its voltage. There is no difficulty therefore in maintaining any desired voltage regardless of the fluctuations in d-c load demand.

As an illustration, this type of voltage control in railway service is being used with the equipment supplied for the electrification of the San Francisco-Oakland Bay Bridge.[8]

By substituting a current coil in place of the voltage coil of the regulator, the same scheme may be used to obtain a load-limiting effect; that is, as the current approaches limiting values, the voltage of the rectifier will be reduced to prevent any further increase in load. This scheme has been used in a number of installations. While they did not employ voltage control this feature together with load limiting could be applied by simply using a voltage regulator and a load regulator working on the same biasing generator.

This same type of control using a counter-electromotive-force generator has been used for voltage regulation of d-c generators. It is, therefore, comparatively simple to operate a d-c generator in multiple with a mercury arc rectifier with any desired load division between the units.

As noted above, grid control of rectifier voltage causes distortion in the a-c power supply and in the d-c output. The amount of this distortion increases with the amount of regulation. When long continued operation at reduced voltage is required, transformer tap changing under load and grid control forms a good combination. The a-c supply voltage is adjusted so that a minimum amount of voltage control with grids is required.

With the advent of the ignitor[9] a competing type of mercury-pool rectifier of the single anode type has become available and is being used quite extensively for various applications. An equipment of this type is made up of a number of separate tubes combined to give the equivalent of a multiple-anode rectifier. Each tube is fired in rotation by an ignitor which serves to start the arc. At the end of each conducting period the tube arc is extinguished and no ionization exists until the main anode again becomes positive with respect to the cathode and the ignitor is re-energized to provide ionization for starting the main anode.

Figure 6 illustrates the essentials of one method for controlling the operation of these tubes. The ignitor, a crystalline compound inserted into the cathode-pool mercury is energized momentarily each cycle to start the main anode. The operation during each cycle is as follows: When a main anode becomes positive with respect to its cathode the auxiliary vacuum tube is made conducting and current is passed through the ignitor. As soon as sufficient ionization is provided an arc is started between the cathode and grid of the power tube short-circuiting the ignitor circuit. This arc in turn starts the main anode. Voltage control is accomplished in the same way as with grid control by delaying the operation of the auxiliary vacuum tube.

The essential feature of this type of control is the provision of a momentary current supply to the ignitor for starting the main arc. In place of the scheme shown by figure 6, peaking transformers and other similar methods may be used,

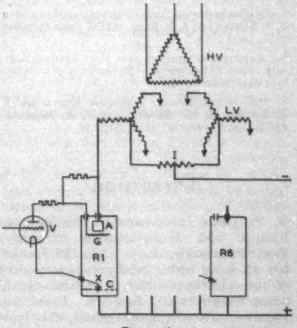

Figure 6

HV—Transformer high-voltage winding
LV—Transformer low-voltage winding
I—Interphase transformer
R1 to *R6*—Individual vacuum tubes
A—Anode
G—Grid
C—Cathode
X—Ignitor
V—Control tube

depending on the requirements of the application.

The foregoing outlines in general terms some of the progress made and some of the practical methods which may be used to control the output voltage of

mercury-arc rectifiers. In general, equipment is now available to regulate the output of a rectifier which will provide the functions of: flat voltage control, under- or overcompound voltage control, voltage control and current limiting, current control, and control suitable for other special applications, such as the equivalent of Ward-Leonard control for starting purposes. The rectifier equipment is thus in most respects as flexible in application as other types of conversion apparatus. The type of equipment to be used, and its control, will depend upon the requirements of the particular installation.

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Discussion

G. F. Jones (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Mr. McDonald has discussed rather briefly voltage control of the ignitron rectifier, a typical circuit being shown in his figure 6. From the point of view of voltage control, this type of rectifier has distinct advantages which I believe should be emphasized.

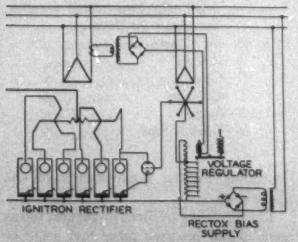

Figure 1. Ignitron rectifier circuit using voltage regulator for current limitation

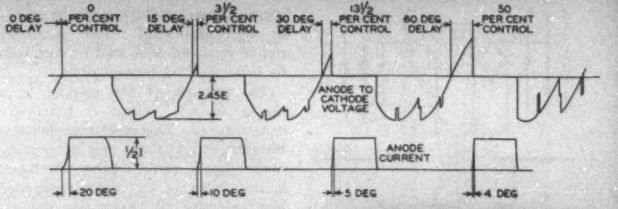

Figure 2. Showing anode-to-cathode voltage and anode currents in function of voltage control and angle of delay

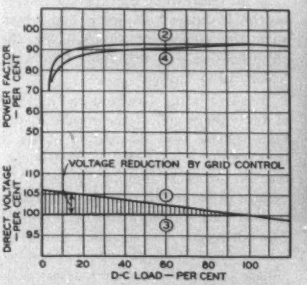

Figure 3. Voltage regulation and power factor of rectifiers with and without grid control

Curve 1—Voltage characteristic (drooping) without grid control

Curve 2—Power factor corresponding to curve 1

Curve 3—Voltage characteristic (level) obtained by grid control

Curve 4—Power factor corresponding to curve 3

As mentioned in the contemporary paper by Mr. Cox and myself, the arc voltage drop of the ignitron is the same for a voltage-controlled and non-voltage-controlled unit. For the conventional rectifier, the presence of the control grids in the arc path increases the arc voltage drop and therefore lowers the efficiency.

The power required by the grids of the excitation tubes of the ignitron is only a fraction of that required by the control grids of the conventional rectifier. This low power requirement extends the flexibility of the apparatus considerably and simplifies the control apparatus. For example, Mr. McDonald's figure 5 shows a motor generator set as a source of bias voltage to effect voltage control of a conventional rectifier. For the ignitron, the corresponding source can be a small Rectox, thus eliminating rotating apparatus and its inherent response time lag. Figure 1 of this discussion shows the essential circuit for high-speed voltage control of an ignitron. The voltage regulator operates to limit the a-c input to the unit to a constant value when the power demand is excessive. A potentiometer is connected across the fixed bias voltage of the Rectox source. The

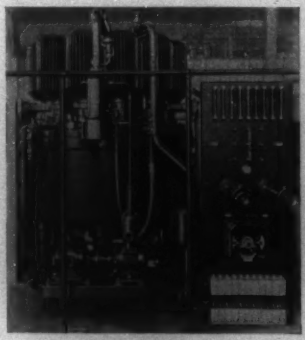

Figure 4. Grid-controlled rectifier installed at a substation of the Commonwealth Edison Company in Chicago

resistance of the effective part of the potentiometer is varied by a Silverstat regulator to insert bias voltage in the neutral of the excitation-tube grid transformer in the correct proportion to limit the current rise. In this circuit the only time lag is that of the moving arm of the regulator.

I would like to ask Mr. McDonald if there is not an error in his figure 6. This circuit shows the ignitor current and the ignitron grid current passing through the same resistor. In order to conduct the ignitor current, this resistor must have a low value. Connected as shown this would permit excessive grid currents both during normal conduction and during arc back.

O. K. Marti (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): It was very gratifying to see from this paper that another manufacturer of rectifiers has adopted the d-c bias grid voltage control and found that it offers many advantages. This method of control was used in connection with our grid-equipped rectifiers as far back as 1930 and has since then been incorporated in rectifiers for many different kinds of applications, as will be seen later on.

I would like to say a few words first in regard to some statements which I feel should be further amplified. For instance, it is said that the grid voltage control imposes some additional duty on the main anodes. It is true that the rectification phenomenon is made somewhat more difficult when the anodes are delayed in their firing due to the fact that the reverse voltage increases more rapidly immediately

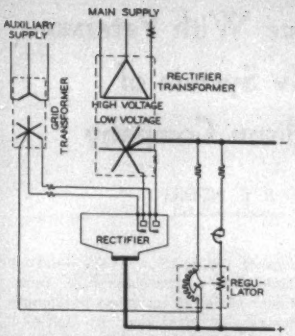

Figure 5. Diagram of connection

duction of voltage, and therefore the angle of delay is practically zero at full load, and becomes larger toward no load, as is shown in figure 3. Curve 1 shows the natural voltage characteristic of an uncontrolled rectifier, while curve 3 shows the flat voltage characteristic which can be obtained by means of grid control. In other words, the reverse voltage increases gradually as the rectifier load is decreased, and consequently there is no additional duty imposed on the anodes in such an application. In order to avoid delay in firing the anodes at full load the transformer taps are chosen accordingly. We therefore wonder to what kind of excess loading of anodes the author had reference.

The only other characteristics affected by grid voltage control and not mentioned by the author are power factors (see figure 3) and the wave-shape distortion of voltage and current of the primary as well as of the d-c system. These factors become quite important as soon as the amount of regulation of voltage is greater than the usual amount as required in railway service. In most applications, however, operation at greatly reduced voltages is not required, except for starting or for temporary periods of operation, as for instance when transferring load from one unit to another, or during very light loads, etc.

In figure 4 of this discussion is shown a 625-volt 5,000-ampere nominally rated 12-anode rectifier with automatic grid control equipment. This equipment was installed in a substation of the Commonwealth Edison Company in Chicago, and has now been in operation for over seven years. The control board is shown on the right-hand side and contains the necessary apparatus, including a quick-acting rocking-type regulator for automatically controlling the output voltage, as well as some rheostats and changeover switches for manual control of voltage.

From figure 5, which shows the simplified diagram of connections of the above installation, it can be seen that no auxiliary motor generator set is used, as in the application shown in figure 5 of Mr. McDonald's paper. However, instead of the generator voltage the rectifier output voltage is used as a source of the d-c bias. Such an arrangement simplifies the control considerably as only a standard potentiometer is necessary.

Figure 6 shows portions of voltage and current graphs taken in the above grid-controlled rectifier installation, which, as mentioned previously, supplies a railway load. These graphs clearly indicate the effectiveness of the grids in keeping the voltage constant in spite of continued fluctuations in the load current (shown in the upper graph). The automatic grid control was turned off at *A*, so that the portion of the (lower) voltage graph to the right of point *A* represents, by contrast, the unregulated fluctuating voltage of the rectifier. It is therefore evident that the output voltage of a rectifier may easily be maintained within as narrow limits as required in spite of fluctuating loads.

Another very interesting installation using this type of grid control was put in operation over two years ago by our Company in New York, furnishing power to the Third Avenue Railway. However, with this rectifier the grid control acts as a current regulator in that its function is to keep the current constant down to the full-load value as long as the base load of the station is above the rated rectifier load. The rectifier is operating in parallel with rotary converters in the same station. It is, however, connected to a different supply bus than the rotary converters. In other words, this installation is also interesting due to the fact that a 1,000-kw rectifier ties together two very powerful networks of 25- and 60-cycle frequencies, which could only be accomplished safely by using, instead of a rotary converter, a rectifier which is not susceptible to frequency or voltage variations.

Furthermore, a d-c bias control with a rocking-type regulator was used in an installation for the Republic Steel Company in Chicago. The arrangement for balancing the load is the same in principle as shown in figure 5, except that the drop across the shunt in the rectifier load circuit was to be used in order to affect the compensating coil of the rocking-type regulator. In

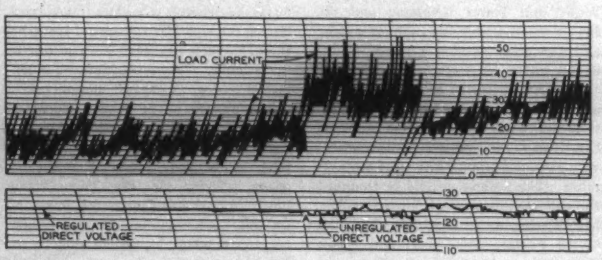

Figure 6. Load charts showing actual voltage regulation obtained with grid-controlled rectifier furnishing power for railway load

Current multiplier—80 Voltage multiplier—5

after commutation takes place, however, as can be seen from figure 2 of this discussion, the anode-to-cathode voltage remains the same in magnitude. Furthermore, the anode currents do not increase appreciably, and therefore a delay in firing does not affect the loading of the anode, see figure 2, which shows the anode current for different angles of delay and percentage of voltage control, respectively.

In most installations where only compounding of voltage is necessary, the re-

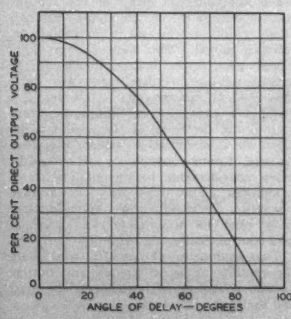

Figure 7 (left). Regulation of direct-voltage output of a six-phase rectifier as a function of the angle of delay

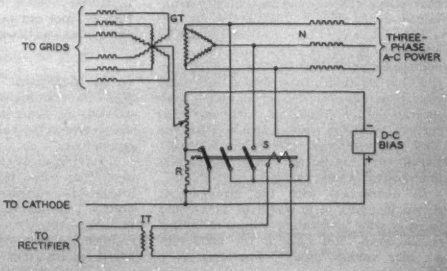

Figure 8. Grid-controlled protection circuit for interrupting short circuits and backfires

connection with this installation it was extremely important to obtain a voltage control over a wide range with quick response due to the requirements of the wire-drawing machines and of the excitation of the machinery in the automatic galvanizing plant. It was found that the d-c bias control on the rectifier met the requirements very well and takes care entirely automatically of a-c and d-c feeder voltage drop and of the inherent machine regulation.

In two radio rectifier plants we probably made the most extensive use of electronic grid control, in that the voltage is regulated from practically zero to the full value. It is general practice in radio installations to apply voltage first at a low value and then to increase it automatically in two or three steps to the normal operating value; see figure 7 of this discussion.

In a rectifier without grids, power is interrupted for protection purposes by means of an a-c circuit breaker in the primary power supply line. In a grid-controlled rectifier, however, additional protection can be provided by means of electronic interruption of power obtained by the blocking action of the grids. This blocking action is dependent upon automatically placing a negative potential in relation to the cathode on all grids when an overload or short circuit occurs in the radio transmitter or rectifier equipment. By using a small high-speed relay to apply the negative grid blocking bias, it is possible to interrupt power in the rectifier unit within a fraction of a cycle. This is considerably faster than the interrupting time required by an a-c circuit breaker, and thus grid control provides much better protection than mechanically operated circuit breakers. Moreover, since an a-c circuit breaker is usually furnished in any event, double protection is provided in that the high-speed grid-control protection apparatus is backed up by the slower-speed circuit-breaker equipment.

Figure 8 shows a diagram of a grid-control protection circuit. Upon the occurrence of a fault in the transmitting equipment, a surge current is induced through insulating current transformer *IT* on the coil of relay *S*. Opening of the back contact of this high-speed relay instantly inserts resistance *R* into the bias potentiometer circuit and thereby causes the negative biasing voltage to be increased to a value of greater relative magnitude than the positive a-c potentials placed on the grids through resistors *N* and grid transformer *GT*. Closing of the other contacts of relay *S* an instant later short-circuits the grid excitation transformer, thus doubly assuring that ony a negative blocking bias is maintained on the grids.

It could be seen from the above that by adding very little extra equipment, an additional possibility of the grid control can be realized. Interruption of short circuits and backfires is accomplished very successfully in connection with our mercury-arc rectifiers furnishing power for the New York subway. Measurements have shown that the backfires are interrupted in less than two cycles.

In connection with the arrangement shown in figure 5, it would be interesting to know what alternating voltage is applied to the grids, and what is the maximum d-c bias voltage used. Furthermore, I would like to know the reason for using energized grids in connection with the arrangement shown in figure 6. It was my understanding that the ignition of the cathode spot can be fully taken care of by the ignitors as developed at present.

G. R. McDonald: I wish to thank Mr. Jones for pointing out an error in the connections of figure 6, and for the further discussion on the voltage control of ignitron equipments.

Referring to Mr. Marti's comments, we agree that when delaying the firing of the anodes of a rectifier to modify the output voltage, the anode currents and voltages remain essentially the same with the same rectifier output. As pointed out by Mr. Marti, rectification is made more difficult when delaying the firing of the rectifier anodes because the inverse voltage increases more rapidly at the end of an anode conducting period. This causes some additional positive-ion bombardment of the anodes. When rectifier loads are light, this is of no consequence. However, if a rectifier is operated at its maximum current rating, and the firing of the anodes is delayed to a considerable extent, this may become of some consequence and should be given consideration in the application of equipment. The type of flat voltage regulation described by Mr. Marti is naturally easy for a rectifier as maximum grid control comes at light load.

The equipment chosen for controlling the rectifier grids to modify the output voltage is entirely a function of the type and range of control desired in each case.

Operating Experience With Petersen Coils on 66-Kv System of Metropolitan Edison Company

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THE Metropolitan Edison Company, operating in the eastern part of Pennsylvania, has a total of 264 miles of 66,000-volt overhead transmission lines, to which interconnections at this voltage with the systems of the Pennsylvania Water and Power Company and the Pennsylvania Power and Light Company add 59 miles, making a total of 323 circuit miles. A single-line diagram of this system is shown in figure 1, which also shows the various types of line construction used, ranging from all-wood construction to all-steel construction, with overhead ground wires and counterpoise. The system neutral is grounded through transformers at West Reading, Middletown, and the Holtwood station of the Pennsylvania Water and Power Company. At West Reading, the grounding bank consists of three single-phase 500-kva 66,000-13,200-volt transformers connected wye-delta, and at Middletown a three-phase zigzag transformer having an equivalent transformer capacity of 1,000 kva. At Holtwood each 66,000-volt line, as shown in figure 1, terminates in a 20,000-kva three-phase 69,000-13,200-volt wye-delta transformer, having the high-voltage neutral grounded through a 300-ohm reactor. The 13,200-volt winding of these transformers is connected to the 13,200-volt station bus.

The system is, in general, equipped with conventional induction types of directional-phase and directional-ground relays. The only exception is in the phase relaying on the Pennsylvania Water and Power Company's lines and on the York end of circuits number 77 and number 78, where directional-distance type relays are used. Balanced relay schemes are used where advantages can be gained thereby.

All lightning arresters and transformers are insulated for full line-to-line voltage.

Application and Design

Interruptions were being experienced on this system due to insulator flashovers, the majority of which were ascribable to lightning, and various means of lightning-proofing these lines were

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The authors wish to express their appreciation of the advice and assistance rendered by E. M. Hunter, of the General Electric Company, in the conducting of tests and in preparation of data.

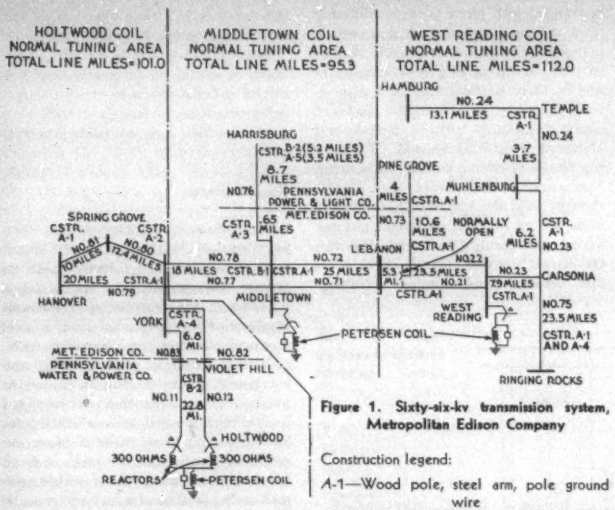


Figure 1. Sixty-six-kv transmission system, Metropolitan Edison Company

Construction legend:

A-1—Wood pole, steel arm, pole ground wire

A-2—Wood pole, steel arm, pole ground wire, overhead ground wire

A-3—Wood pole, steel arm, pole ground wire, overhead ground wire, expulsion gaps

A-4—Wood pole, wood arm, no pole ground wire

A-5—Wood pole, steel arm, pole ground wire, expulsion gaps, counterpoise

B-1—Steel tower, no overhead ground wire

B-2—Steel tower, two overhead ground wires, counterpoise

considered. It was found, however, that approximately 50 miles of double-circuit line, which was originally built for operation at 33,000 volts, could not be changed to accommodate either overhead ground wires or expulsion gaps without complete rebuilding. An analysis of the operation for the year 1936 showed that approximately 69 per cent of the faults were cleared by ground or phase and ground relays. Numerous conductor failures and insulator failures during lightning storms were experienced. It was therefore finally decided to install Petersen coils, or ground fault neutralizers, on this system, with the expectation that over 70 per cent of the outages would be eliminated. Due to operating conditions, and in order to maintain selective relaying under all conditions, it was necessary to install a coil at each location where the system neutral was grounded.

The neutral bushing of the zigzag grounding transformer at Middletown was originally rated at 15 kv. This was replaced with one rated 50 kv, in order to provide insulation capable of handling at least line-to-neutral voltage. No other change of system insulation was necessary on account of the Petersen-coil application.

The three Petersen coils were furnished by the General Electric Company and were designed from measurements of charging current made by disconnecting the grounding transformers at West Reading and Middletown and opening the neutral-ground connections at Holtwood, and grounding one phase of the system through a current transformer. This measurement was made at various locations on the 66,000-volt system. The average charging current per mile of circuit was found to be 0.34 amperes.

In the application of three Petersen coils, it was decided to have each coil normally protect approximately one-third of the total circuit mileage and to have sufficient range to allow for any abnormal operation which could be anticipated.

All of the coils were designed for ten-minute operation, those at West Reading and Middletown having ratings of 15 to 60 amperes, and the Holtwood coil having a rating of 12 to 48 amperes. The minimum current rating was selected to permit operation of the minimum expected circuit mileage and maximum rating selected to allow for system growth. The West Reading and Middletown coils are designed with single bushings, conservator tanks, Thyrite by-pass resistors, current transformers inside the tank in the grounded lead, and external manually-operated ratio adjusters by means of which 25 tap points are obtainable. The Holtwood coil is similar, except that a gas seal is used instead of the conservator.

Each coil was provided with an oil circuit breaker which would automatically short-circuit the coil after current had passed for a predetermined time, thereby solidly grounding the system neutral to allow relaying of the faulty line. Figure 2 shows the Middletown coil and short-circuiting oil circuit breaker as installed, together with the grounding transformer in its original position.

The auxiliary-control apparatus for each coil consists of an instantaneous overcurrent self-reset relay, a timing relay, an operation counter, a signal, and a recording ammeter, connected as shown in figure 3. Operation of the overcurrent relay simultaneously energizes the timing relay and the operation counter. The timing relay is a d-c motor-operated device used to close the short-circuiting oil circuit breaker if current flows through the coil continuously for a period of five seconds. The timing relay returns to the starting position instantly if the fault is cleared within the five-second period. The operation-counter registers the number of operations of the overcurrent relay. This provides a more accurate record of the total number of faults, as several faults occurring within a short space of time would appear as a single fault on the recording ammeter, due to the slow

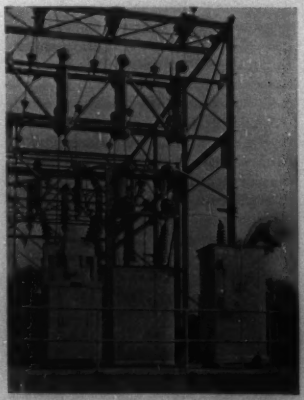


Figure 2. View of Petersen coil and short-circuiting oil circuit breaker installed at Middletown

chart speed. At West Reading and Middletown, the signal is connected as shown in figure 3, and is energized only when the short-circuiting oil circuit breaker closes. At Holtwood, it is connected in parallel with the timing relay, becoming energized directly from the overcurrent relay contact.

Tuning Tests

The coils were installed in September 1937, and immediately after their installation tuning tests were made to determine the proper operating taps for the various operating conditions. Normal tuning areas were established, as shown in figure 1, and each coil was tuned to its respective area without placing a fault on the system, in the manner described in a recent AIEE paper.[1] In these tests it was found that the resonance or "in tune" current values were high, in some cases far exceeding the continuous current rating of the coils. This high resonance current was thought to be due to excessive electrostatic unbalance of the transmission lines, and indicated that transpositions would be necessary. The effect of the various transpositions was calculated and the transpositions made as described recently in an AIEE paper.[2]

Transpositions

Referring to figure 1, circuits numbers 21 and 22 between West Reading and Lebanon, and circuits numbers 71 and 72 between Lebanon and Middletown, were given one complete transposition. The section of circuits numbers 77 and 78 between York Haven and York, which is about two-thirds of their length, was rearranged with phase positions differing from one another and from that section between Middletown and York Haven, so that, in effect, with both circuits in service there is one complete transposition. The bottom and middle phases of circuit number 24 between Temple and Hamburg were interchanged. The two top phases of circuit number 80 between York and Spring Grove were interchanged, and also the two phases on the same side of the pole on circuit number 81 between Spring Grove and Hanover. On circuit number 82, which is a tie line between this company's substation and that of the Pennsylvania Water and Power Company in York, the vertical phasing was changed from *C-B-A* to *B-A-C*. On the Pennsylvania Water and Power Company's system, the top and middle phases of circuit number 11 between York and Holtwood were interchanged. In making these changes, advantage was taken of locations at which the configuration of the circuit changed from vertical to horizontal arrangement, so that the total additional material required for all transpositions consisted of two 14-foot steel crossarms.

The effect of the transpositions was, in some cases, to balance one circuit against another in a given section of the system, which meant that the outage of one circuit in such a section would cause some degree of electrostatic unbalance. If the coils were retuned to the remainder of the system by changing taps, this electrostatic unbalance might be sufficient to cause excessive resonance current to flow through the coils, and a certain amount of detuning would then be necessary. From an operating viewpoint, it was considered preferable to drop the circuit without attempting any retuning, inasmuch as the amount of detuning caused thereby was less than that which was successfully handled in field tests.

After the transpositions, etc., were made, a second set of tuning tests was carried out, and resonance current magnitudes were found to have been reduced to a point which was considered acceptable.

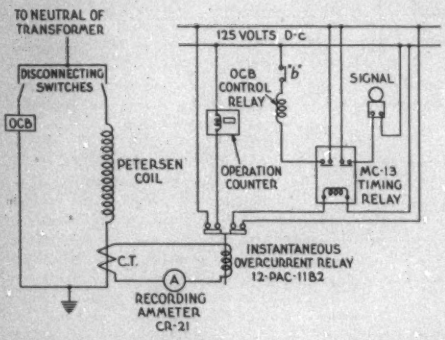


Figure 3. Connections for auxiliary control equipment

Staged Tests

An automatic oscillograph was then installed at Middletown, and staged tests were conducted. Arcing faults to ground were initiated by connecting a 0.5-ampere fuse wire across a five-unit insulator string suspended from a steel crossarm located on a wood pole, grounded through a down-wire, and energizing this by closing an oil circuit breaker. This down-wire was wrapped several times around the base of the pole, but no attempt was made to lower the pole-footing resistance. A series of seven tests was conducted, six of which were with arcing faults and with system conditions varying from normal tuning to as much as 25 per cent out of tune. The out-of-tune conditions were established by isolating certain lines from that part of the system on which the tests were being conducted, leaving, in some cases, only two coils to clear the fault. No changes of coil taps were made from the normal position for any of the out-of-tune tests. The other test was a solid ground fault, made in order to check the operation of the short-circuiting breakers and the system ground relays. In the arcing-fault tests, the arc was suppressed in each case without any oil-circuit-breaker operation or system disturbance,

Table I. Petersen Operating Record

	Total	Per Cent of Total	Per Cent of Transient
All faults	190	100.0	
Transient faults	173	91.0	
Transient faults cleared by Petersen coil	128	67.4	74.0

Table II. Cause of Transient Faults Cleared by Petersen Coils

Lightning	84
High wind, rain, sleet, etc.	18
Unknown (fair weather)	18
Bushing flashovers	6
Iron oxide on insulator	1
Broken conductor contacting steel tower	1
Total	128
Per cent of total due to lightning	65.6

1. For all numbered references, see list at end of paper.

the time of extinguishing the arc varying from one-half cycle to seven cycles.

Operating Results

The coils were placed in service October 16, 1937, and in the various tables, "Petersen-Coil Year" designates the year ending October 15, 1938. Table I shows that out of a total of 190 faults occurring during the Petersen-coil year, 128 faults were cleared by the coils without oil-circuit-breaker operation. However, the operation-counters, and the oscillograph which was in service for several months at Middletown, show that actually there were more than 500 arc suppressions. The oscillograms reveal that every fault was not cleared by the coils at the first attempt, as in some cases several arc suppressions occurred in a fraction of a second on the same phase before the fault was completely removed from the system. In these cases, the coils were given credit for clearing only the initial fault, as a system disturbance resulting in oil-circuit-breaker operation would have begun at that time, had the coils not been in service.

As previously stated, it was expected that the coils would remove over 70 per cent of all faults from the system without disturbance. The results show that 67.4 per cent of all faults (74.0 per cent of all transient faults) were cleared by the coils without oil-circuit-breaker operation.

The fact that results have been somewhat lower than was expected, is due, in part, to an unusual condition existing on circuits numbers 71 and 72, where they pass close by an ore-concentrating plant

Table III. Comparison of Faults and Oil-Circuit-Breaker Operations Before and After Petersen-Coil Installation

	Average of Previous Five Years	Petersen-Coil Year
Total faults	164	190
Total transient faults	138	173
Transient faults causing oil-circuit-breaker operation	138	45
Permanent faults	26	17
Total oil-circuit-breaker operations	448	221
Oil-circuit-breaker operations from transient faults	315	118

of a large steel company. At this point, under certain weather conditions, the black oxide of iron dust discharged from the stacks deposits on the insulators and reduces their insulation level. Consequently, a single conductor-to-ground fault at another location, with the accompanying increased voltage-to-ground on the two sound phases, caused the dirty insulators to flash over, resulting in simultaneous faults at different locations involving more than one phase. Faults of this nature occurred on several occasions before the cause was determined. Increasing the insulation level in the affected area has apparently remedied this serious condition, as no simultaneous faults have since been experienced; furthermore, to the best of our knowledge, neither has there been a flashover in the vicinity of the concentrating plant.

An analysis of the fault-clearing record of the coils is given in table II. It will be noted that 84 of the 128 faults cleared by the coil were caused by lightning. Approximately two-thirds of the 18 operations from unknown causes occurred around daybreak, and were believed to have been caused by birds.

A comparison of the number of faults and oil-circuit-breaker operations before and after the Petersen-coil installation is given in table III. Although the total number of faults during the Petersen-coil year exceeded the five-year average, the total number of oil-circuit-breaker operations was reduced more than 50 per cent. This performance makes it apparent that oil-circuit-breaker maintenance has been materially reduced.

The over-all reduction of system disturbances is clearly shown by the fact that the total number of transient faults causing oil-circuit-breaker operation has been reduced from an average of 138 per year, over five years, to 45 during the Petersen-coil year, or a reduction of 67.4 per cent. Lightning was responsible for 36 of the 45 faults, 29 of which were cleared by phase relays. The majority of these faults, however, occurred in the 50-mile section of double-circuit line with closely spaced conductors. Lightning, therefore, was responsible for a total of 120 transient faults, 70 per cent of which were cleared by the Petersen coils. The reduction in oil-circuit-breaker operations caused by transient faults was about 64 per cent.

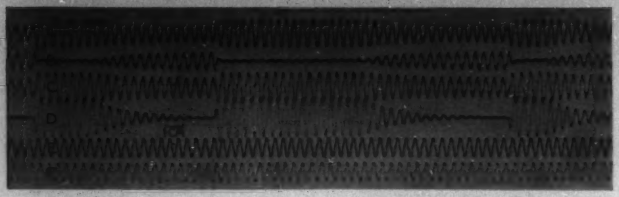
It is also interesting to note that during the Petersen-coil year the total number of permanent faults was only about two-thirds of the five-year average (table III). It seems reasonable to credit this reduction to the coil performance, inasmuch as fewer insulator failures and conductor failures were experienced during the coil year than in any one of the previous five years.

The number of interruptions per circuit during the Petersen-coil year, in

Table IV. Interruptions Per Circuit

Circuit Number	Number of Circuit Interruptions: Average of Previous Five Years — Lightning	Other Causes	Total	Petersen-Coil Year — Lightning	Other Causes	Total	Construction (Figure 1)	Type of Insulators	Equivalent Spacing (Inches)
11							B-2	Suspension	
12							B-2	Suspension	
21	10.4	5.4	15.8	7 (1)	3	10 (1)	A-1	Pin	45
22	12.8	4.4	17.2	5	9	14	A-1	Pin	45
23	1.6	1.2	2.8	0	1	1	A-1	Pin and suspension	66
24	1.4	2.2	3.6	5	1	6	A-1	Pin	61
71	16.2	8.2	24.4	5	6	11	A-1	Pin	60
72	13.2	6.8	20.0	6 (1)	9	15 (1)	A-1	Pin	60
75	3.6	3.4	7.0	5 (1)	1	6 (1)	A-1 and A-4	Pin	54
76							A-3, A-5, B-2	Suspension	
77	6.6	1.6	8.2	0 (1)	0	0 (1)	B-1	Suspension	153
78	8.6	2.2	10.8	0	1	1	B-1	Suspension	153
79	8.2	5.0	13.2	1	1	2	A-1	Suspension	94
80	4.6	3.0	7.6	1	0	1	A-2	Suspension	100
81	6.0	4.0	10.0	1	1	2	A-1	Suspension	100
82	2.6	1.0	3.6	1	0	1	A-4	Suspension	91
83	2.4	1.2	3.6	0	0	0	A-4	Suspension	91
Totals	98.2	49.6	147.8	37 (4)	33	70 (4)			
Summary									
Pin-type insulators	57.6	30.4	88.0	33 (3)	29	62 (3)	148 circuit miles		
Suspension insulators	39.0	18.0	57.0	3 (1)	3	6 (1)	147 circuit miles		
Combination pin and suspension	1.6	1.2	2.8	0	1	1	14 circuit miles		

NOTE: Figures in parentheses represent additional interruptions occurring while coils were short circuited and therefore inoperative.



comparison with the average of the previous five years, is shown in table IV. This record shows that the performance of the circuits having closely-spaced conductors and pin-type insulators has been considerably below expectations. On the other hand, the performance of the circuits with five-unit suspension insulators has been excellent. It is probable that part of the reason for the poor performance of the pin-insulator circuits lies in the high pole-footing resistance, which in the event of surge current passing to ground, would cause the potential of the entire pole structure to be raised above ground potential sufficiently to cause multiple flashovers on the same structure. Spot measurements of pole-footing resistance, recently made along circuits numbers 21 and 22, were found to vary between 25 and 150 ohms, with an average from 20 locations of 80 ohms. Further study is being made of the pin-type circuits, in an effort to improve their operation.

Data on circuits numbers 11 and 12, of the Pennsylvania Water and Power Company's system, have been omitted from table IV because of certain changes in line protection made about two years prior to the coil installation. Likewise, circuit number 76 has been omitted due to its having been in use less than one year prior to the coil installation.

Summarizing the data in table IV, comparing the Petersen-coil year with the average of the previous five years, it will be seen that the reduction of interruptions to pin-type insulator circuits was 27 per cent; of suspension insulator circuits, 88 per cent; and of the combination pin- and suspension-insulator circuits, 64 per cent. Of all circuits, a reduction of 51 per cent was obtained.

On four occasions, during severe lightning storms, the system became separated by a permanent fault between Middletown and West Reading, resulting in two systems protected by Petersen coils. On each occasion, one or more subsequent flashovers were cleared in each section with the normal coil tap. In one case this represented an out-of-tune condition of nearly 30 per cent.

Figure 4. Oscillogram showing fault due to tree contact

A—Line-to-neutral voltage, phase A; 1 CM = 60 volts root-mean-square (×600)
B—Line-to-neutral voltage, phase B; 1 CM = 60 volts root-mean-square (×600)
C—Line-to-neutral voltage, phase C; 1 CM = 60 volts root-mean-square (×600)
D—Petersen-coil current; 1 CM = 12.0 amperes root-mean-square (×1)
E—Line-to-line voltage, phase A-B; 1 CM = 100 volts root-mean-square (×600)
F—Line-to-line voltage, phase B-C; 1 CM = 100 volts root-mean-square (×600) (measured maximum to maximum)

Three rather peculiar instances in which the Petersen coils saved the system from major disturbances may be worthy of reporting:

1. During a high wind storm, a tree growing close to circuit number 71 was blown into the line, causing 41 coil operations within a period of 25 minutes, although no system disturbance of any kind was observed. The evidence was found by the patrol crew on the following day. Figure 4 shows a section of an oscillogram obtained during this fault, showing three of the 41 arcs extinguished in various times during a period of approximately one second.

2. A bushing on an oil circuit breaker connected to the 66-kv bus at West Reading broke down and arced to the ground sleeve inside the oil tank. This resulted in five coil operations within a period of a few seconds. Although at the time of the coil operation puffs of smoke were seen in the 66-kv switching structure by the station operator, the cause of the operations was not located until two days later when the oil circuit breaker was opened for overhauling. Again, there was no disturbance on the system. Figure 5 is a section of an oscillogram of this fault, showing that one of the flashovers cleared in less than one-half cycle.

3. A dead-end loop on a steel tower, which at some previous time had been burned by a flashover, broke during a high wind, and the side having the splicing clamp on the end of the wire swung intermittently into the tower. This resulted in a total of 265 coil operations over a period of one hour. During this time the trouble was located and the faulty section isolated, all of which took place with no disturbance to service or line-to-line voltage. The oscillogram of this fault showed phenomena similar to that which took place during the tree fault (figure 4), although in some instances more frequent contacts occurred.

In figure 6 is shown an oscillogram of a typical "unknown" cause of coil operation which was cleared in approximately 2½ cycles. This operation occurred at 5:31 a.m., and was suspected to have been caused by birds.

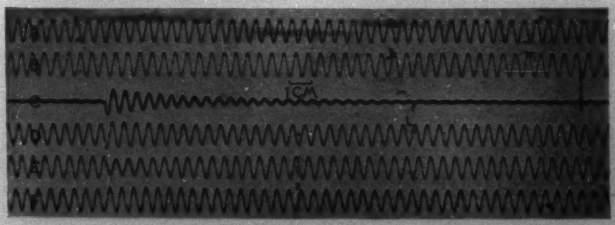
It is important to note that from numerous oscillograms obtained showing arc suppression by the coils, in no case did the line-to-ground voltage on either of the two sound phases exceed the line-to-line voltage.

Permanent Ground-Fault Relaying and Coil Short-Circuiting Breaker Operation

In order to maintain proper selectivity in the operation of ground relays on

Figure 5. Oscillogram showing fault due to failure of circuit-breaker bushing

A—Line-to-line voltage, phase A-B; 1 CM = 100 volts root-mean-square (×600)
B—Line-to-line voltage, phase B-C; 1 CM = 100 volts root-mean-square (×600)
C—Petersen-coil current; 1 CM = 6.5 amperes root-mean-square (×1)
D—Line-to-neutral voltage, phase A; 1 CM = 60 volts root-mean-square (×600)
E—Line-to-neutral voltage, phase B; 1 CM = 60 volts root-mean-square (×600)
F—Line-to-neutral voltage, phase C; 1 CM = 60 volts root-mean-square (×600) (measured maximum to maximum)



the system, it was, of course, necessary to take care that the coil short-circuiting breakers at all three locations would close at approximately the same time. The d-c motor-operated timing relays used for this purpose were found to be remarkably consistent, and no particular difficulty was experienced in this respect. All coil breakers are reopened manually on order of the system operator.

Only one incorrect oil-circuit-breaker operation was attributed to dissimilar closing times of the coil breakers. In this case a single conductor-to-ground flashover occurred on circuit number 78, which was not cleared by the coils within the five-second period. The coil breakers then closed automatically and circuit number 78 was relayed at both ends, together with the York end of circuit number 77, all by ground relays. It was found that the Middletown coil breaker was about 30 cycles slower than the Holtwood and West Reading coil breakers, the effect of which was to delay tripping at Middletown long enough to allow tripping of circuit number 77 at York. Incidentally, this was the only case observed where a single conductor-to-ground fault was not cleared within the five-second period. It has been suggested that this time be increased in view of experiences with other installations.[3] This cannot be done at present because of eight-second time-delay no-voltage relays connected to coupling capacitor potential devices at a station fed from circuit number 72.

The ground relays on this system are of the directional and nondirectional overcurrent types, most of which have been in service for nearly 15 years. To date, no changes of any nature have been made to the ground-relay schemes or settings on account of the Petersen-coil installation. The 66-kv system relaying, in general, during the Petersen-coil year has been satisfactory, being on a par with the relaying during the previous years.

In two instances, balanced ground relays have operated along with phase relays to clear double-circuit multiple flashovers-to-ground, although none of the coil breakers had closed before the fault was cleared. Further investigation is being made in an effort to determine the reason for these ground-relay operations.

With multiple-coil operation, it is apparent that if any one coil is short-circuited, all other coils are rendered ineffective, as the system is then solidly grounded. Therefore, it is not only important that all coil breakers close at the same time, but it is also important, in the case of manual reopening, that they be reopened in the proper order; otherwise improper relaying might take place for subsequent faults occurring before all coil breakers have been reopened. On our system, this condition is almost entirely avoided by not reopening Middletown coil breaker until after the other two coil breakers have been reopened.

In some cases, particularly during electrical storms, an appreciable time elapsed before all coil breakers were reopened, during which faults occurred subsequent to the one causing the coil-breaker closures, causing interruptions that might otherwise have been avoided. A total of seven ground faults occurred in such periods during the Petersen-coil year, four of which caused circuit interruptions. Therefore, in order to get all coils back into service as quickly as possible, plans are under consideration to install automatic-reopening equipment on the coil breakers. This equipment will function to reopen the coil breaker after fault current has ceased to flow in the grounding transformer.

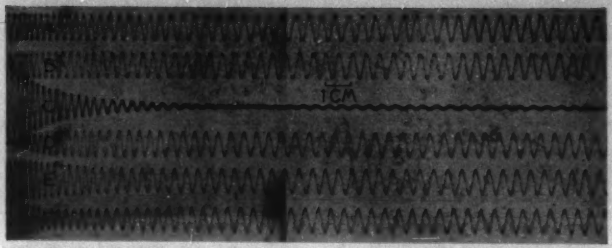


Figure 6. Oscillogram showing flashover from unknown cause

A—Line-to-line voltage, phase *A-B*; 1 CM = 100 volts root-mean-square (×600)

B—Line-to-line voltage, phase *B-C*; 1 CM = 100 volts root-mean-square (×600)

C—Petersen-coil current; 1 CM = 6.5 amperes root-mean-square (×1)

D—Line-to-neutral voltage, phase *A*; 1 CM = 60 volts root-mean-square (×600)

E—Line-to-neutral voltage, phase *B*; 1 CM = 60 volts root-mean-square (×600)

F—Line-to-neutral voltage, phase *C*; 1 CM = 60 volts root-mean-square (×600) (measured maximum to maximum)

Conclusions

From experience obtained thus far, the following appear to be reasonable conclusions:

1. The amount of electrostatic unbalance of a system should first be determined before a coil installation is planned.

2. Experience with multiple-coil installation indicates that the addition of a suitable automatic-reopening device for the short-circuiting oil circuit breakers is desirable.

3. Multiple-coil operation has presented no serious difficulty from the standpoint of system relaying.

4. On lines of fairly modern construction, with five suspension disk insulators, the improvement in service is up to expectations.

5. On lines of older construction, using pin insulators, the improvement is not so marked, indicating, we believe, that more multiple flashovers occur on these lines.

6. It is apparent that successful Petersen-coil operation may be expected with the coils appreciably out of tune. Under abnormal system operation, one section of the system operated with two coils as much as 30 per cent out of tune, during which time successful operations were recorded.

7. Operation of the coils has been responsible for a reduction in the total number of oil-circuit-breaker operations, with a consequent reduction in maintenance cost.

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Discussion

E. M. Hunter (General Electric Company, Schenectady, N. Y.): It is worthy of note that the grounded-neutral method of operation has been supplemented by Petersen coils on the Metropolitan Edison Company 66-kv system. This is one of several applications of its kind in the United States and there are indications of a very definite trend in the industry away from the solid neutral ground with its very obvious limitation that every flashover to ground is a short circuit requiring immediate attention. It is believed that the

presentation of the operating experience given in this paper is very timely and should be of considerable value to others who may be considering similar applications.

It is expected that from time to time other companies which are now operating solidly grounded will supplement their ground fault protection with Petersen coils. This requires some system planning because certain insulation levels must be maintained in the connected electrical apparatus. Transformer neutrals should be fully insulated, lightning arresters should be of the ungrounded-neutral type, and interconnections of systems of different voltage levels should be through two-winding transformers and not autotransformers. These facts should be kept in mind when new purchases of electrical apparatus are contemplated because otherwise the cost of rebuilding equipment to make it suitable for the Petersen coils may make the application uneconomical.

E. H. Bancker (General Electric Company, Schenectady, N. Y.): One of the factors brought to light in this paper is the fact that the use of Petersen coils does not upset normal ground relaying. It should be pointed out that this does however require that when the coils are short-circuited, there should be about as many grounded neutrals as existed at the time the relay settings were made, or else the relays will have to be reset for the new ground-fault current condition. This factor must be considered when an installation is proposed in order to determine whether certain neutrals previously grounded and not to be equipped with coils also should be provided with grounding circuit breakers.

The control for automatically reopening the breaker may be arranged to perform in any one of several possible ways. In my opinion the circuit breakers should reopen immediately when the coil current ceases in order that the system shall return to Petersen-coil operation as quickly as possible. It seems to me that the breaker should also reopen after it has been closed a definite time that is long enough to assure relay operation even though the ground current is still flowing, so that in the event of relay failures the system will return to Petersen-coil operation rather than maintain ground-fault current. Of course, this means continuous-rated coils or action by the operators to isolate faulty sections before the coil thermal limits are exceeded. It would seem preferable to operate with the Petersen coils in service and one conductor grounded in the event of relay failure, rather than allow the system to continue to supply ground-fault current until breakers are opened manually. The opinion of others on this point is solicited. It would be helpful to the manufacturers in planning future applications and in the interest of standardization.

H. K. Sels (Public Service Electric and Gas Company, Newark, N. J.): The application of Petersen coils to a system must be studied very carefully to determine if the benefits which may be derived are great enough to justify their installation. Messrs. Rankin and Neidig have reported in table IV the interruptions which have been experienced per circuit over a number of years. This tabulation shows that circuits numbers 21 and 22, 71 and 72 have between 60 and 80 interruptions per 100 miles per year so that the pole ground wire apparently has no beneficial influence on the number of interruptions and in fact may have the opposite effect. However it is evident that the presence of this ground wire does give a preponderance of single-phase faults which presents an ideal situation for the successful operation of the Petersen coil.

In studying a section of our system for the application of the Petersen coil, it was found from an analysis of several hundred oscillograms that approximately 80 per cent of the faults started on more than one phase so that only 20 per cent of the faults remained as single phase for a Petersen coil to clear. It is therefore felt that in order to obtain sufficient improvement in line performance that the successful application of a Petersen coil also required a large item of expense in a general reconstruction of most of the lines to increase the proportion of the single-phase faults. Since in connection with the reconstruction protector tubes could be applied more cheaply than the Petersen coil, it was decided that the Petersen coil should not be installed.

I believe that it would contribute considerably to the paper if Messrs. Rankin and Neidig would submit additional information on the proportion of single-phase faults which they believe occur on their line construction. This should show that the installation of the Petersen coil was justified in their case whereas our analysis casts a reasonable doubt on the over-all gain to be obtained by a Petersen-coil installation.

J. R. North (Commonwealth and Southern Corporation, Jackson, Mich.): This paper is very interesting and shows clearly the results obtained by the use of Petersen coils on this system. It further substantiates our opinion, based upon tests and operating experience, that there are many factors which need to be considered carefully in determining the probable effectiveness of Petersen coils in a given application. These include evaluation of

(*a*). Relative number of single line-to-ground faults versus faults involving two line conductors.

(*b*). Relative number of permanent ground faults versus transitory ground faults.

(*c*). Magnitude of the in-phase component of fault current (due to line resistance, insulator leakage, corona, etc.) and influence of voltage recovery rate.

(*d*). System arrangement—radial, loop, multiple lines, relative location of lines.

(*e*). Dynamic and transient overvoltages as may occur with faults at different locations, and the ability of the system insulation to withstand them.

(*f*). Protective relay scheme and necessity for automatically clearing permanent ground faults.

In this connection it may be of interest to mention two rather detailed studies of extensive transmission systems, one operating at 138 kv and the other at 44 kv. On the 138-kv system, calculations indicate what we consider to be an excessive amount of uncompensated fault current if Petersen coils were to be used and there is as yet no definite evidence available to establish the upper limit of permissible magnitude of such fault current under the expected conditions of recovery voltage. Furthermore, rapid and accurate isolation of permanent ground faults would be difficult since the system is quite extensively interconnected. The relative advantages and limitations of various types of operation were carefully evaluated and it was decided to operate this system with the neutral effectively grounded.

The 44-kv system on the other hand consists essentially of a number of radial star-type units, connected together by single lines which may be operated as independent sections. This system appears to lend itself admirably to the use of Petersen coils.

John A. M. Lyon (The Johns Hopkins University, Baltimore, Md.): The experience with iron oxide depositing on pin-type insulators and the consequent reduction in insulation strength suggests the importance of further study on the effects of soot and other deposits on insulation.

It is important to note that the Petersen-coil protection for that part of the transmission system which had closely spaced conductors with pin-type insulators (low insulation level) has been definitely inferior to the protection afforded to the rest of the system consisting of lines of modern construction. Undoubtedly the high pole-footing resistance was also a factor in the relatively lower degree of protection which was afforded to these closely spaced lines. This condition immediately emphasizes the necessity for the consideration of the likelihood of single line-to-ground faults developing into double line-to-ground faults or line-to-line faults. Unfortunately, sufficient information on this subject is not always available. The usual relay records will of course give the past history of a transmission line by classifying line-to-line faults, and line-to-ground faults, but there is no way of knowing (except through the use of an automatic oscillograph) how many of the first type of faults have developed from the second type. It indicates that increased attention should be placed on the possibility of multiple faults developing from single line-to-ground faults. A consideration of the actual construction of the lines in subsequent installations seems warranted, and judgment should be based on such practical information as the present authors have given.

F. Von Voigtlander (Commonwealth and Southern Corporation, Jackson, Mich.): Messrs. Rankin and Neidig report a rather successful application of Petersen coils under somewhat adverse conditions. The system to which the coils were applied had previously been operated grounded through rather high reactances at several stations. Line conditions no doubt were largely responsible for the number of multiple faults experienced, though this may have been increased somewhat by the high neutral reactances. Since nothing would be gained by totally isolating the neutral, and solidly grounding would not be considered because of the condition of the lines and because of some radial services, the application of Petersen coils became a logical consideration for this system.

The important criterion upon which to base performance expectations of Petersen coils becomes the proportion of transitory single line-to-ground faults to all faults

experienced on the system. On lines of small phase spacing, multiple flashovers would tend to be a rather large proportion of the total, and for such faults the Petersen coils would be of value only in that they would probably tend to limit overvoltages from single line-to-ground faults and thereby to some extent mitigate the probability of second faults occurring, as is brought out by the operating experience cited by the authors.

A reasonable balance to ground is desirable on any transmission system, and it is essential where Petersen coils are involved. This is forcefully demonstrated by this application, in which the unbalance to ground was found to be so great as to overload the Petersen coils during normal system operating conditions.

When more than one Petersen coil must be short-circuited for permanent ground-fault isolation, it is necessary to delay all ground-relay action until short-circuiting of the coils involved has been completed. This requirement is believed to restrict the application of multiple Petersen coils on extensive and complicated networks, particularly where large ground-fault currents may be experienced.

Two instances are mentioned by the authors of balanced ground and phase relays operating to clear multiple ground faults before the Petersen coils had been by-passed. Was this not due to the faults being on different phases at different locations on the system so that residual currents could flow between them large enough to trip balanced ground relays, and even phase relays, thereby clearing the faults before sufficient time had elapsed for the by-passing switches to operate?

H. M. Rankin and R. E. Neidig: In closing the discussion, the authors wish to express their appreciation of the interest shown in the subject and the comments brought out in the various discussions.

Referring to the discussion by Mr. Sels, the results of a study of interruptions caused by lightning during the year 1936 showed that 47 per cent were cleared by ground relays only, 13 per cent by both phase and ground relays, 31 per cent by phase relays only, and 9 per cent with no relay indication. This analysis was based purely on relay-target indication, and shows that at least 60 per cent of all interruptions involved ground, with a possibility of a good share of another 9 per cent.

Undoubtedly pole ground wire does assist in confining flashovers to line-to-ground, and therefore allows successful coil operation. However, our experience indicates that even with pole ground wires on pin-insulator circuits, it is essential to have low pole-footing resistance in order to avoid multiphase flashovers. On circuits with higher insulation levels (suspension insulators, wood pole), the pole-footing resistance does not appear to be as important a factor in obtaining successful coil operations. An investigation is now being made to determine the necessary requirements for lowering the pole-footing resistance on the pole lines having pin-type insulators.

Mr. Von Voigtlander has expressed an impression that the 66-kv system had previously been grounded through rather high reactances, which may have been partially responsible for the number of multiple flashovers. Although the interconnection power transformers at Holtwood were grounded through high reactances, it is to be pointed out that the grounding transformers at both Middletown and West Reading were operated with solidly grounded neutrals.

From operating experience prior to the coil installation, it was suspected that the improvement in operation of the circuits having closely spaced conductors would not be so marked, which suspicion has been substantiated by the first year's operating record. However, it is expected that this condition will improve from time to time due to the fact that bad poles, having closely spaced conductors, are replaced with new poles, affording greater spacing.

In Mr. Von Voigtlander's opinion, with multiple-coil installations it is necessary to delay all ground-relay action until all coils involved are short-circuited. The authors wish to emphasize that on the Metropolitan Edison Company system no additional delay was introduced to any ground relays above that which existed prior to the installation of the Petersen coils. In the authors' opinion, the determination of ground-relay settings will, in general, not be affected by the use of Petersen coils. It is agreed, however, that greater precautions are necessary in this respect when the system involved is in the form of a multiple-grounded ring, rather than a straight-line or radial system as was the case of the Metropolitan Edison Company. For a single-coil installation, no difficulty should be experienced in this respect with either type of systems.

In connection with the two instances of balanced ground-relay operations reported, further investigation showed that quite possibly they were due to faults being on different phases of the two circuits on the pole line involved, as was suggested by Mr. Von Voigtlander. However, it is definite that these faults occurred within the confines of the pole line involved, inasmuch as circuit-breaker operation occurred only on these lines, which suggests the probability that the multiple-circuit fault occurred on a common-pole structure.

The authors agree with Mr. Bancker's opinion concerning automatic reopening of coil short-circuiting breakers when neutral current ceases to flow. Whether or not the coil breaker should also reopen automatically after a definite time, even though neutral current is flowing, is open to question. We believe the adoption of this function would be governed by the operating policies existing prior to the coil installation, and the desirability of continuing such policies. In our case, a circuit-ground-relay failure throws the responsibility for removing the short circuit from the system back to a relay connected in the neutral of the grounding transformer, which, after a definite time delay, operates a warning signal to the station operator. If the operator is then unable to clear the fault within a definite time, the grounding transformer is then disconnected from the system automatically. It is our impression that the increased cost for a continuously rated Petersen coil would far exceed the cost of the equipment required for the above scheme, which we have found to be desirable protection for all grounding transformers.

The following are unusual instances which have occurred since the original paper was written:

1. Piece of fence wire on conductor near insulator was blown into crossarm by wind. Counters recorded over 600 successful operations (each coil) over period of one hour and 23 minutes. West Reading coil breaker was finally closed manually and faulty line (number 75) tripped successfully upon next contact. Film in oscillograph ran out after 162 arc suppressions.

2. During high wind, foreign object (unknown) on pole structure of numbers 21 and 22 circuits, apparently contacting crossarm, caused 220 arc extinctions within 12 minutes, as taken from the oscillograph. Counter readings indicated an average of 51 operations. After 12 minutes the coil breakers operated, clearing the fault, although evidence from the oscillogram showed that an arc had been extinguished a few cycles after the coil breaker received the impulse to close; otherwise an indefinite number of subsequent coil operations would have occurred. This was only the second instance in about 1½ years' operation which indicated the possible desirability of an increased time delay in closing the circuit breakers short-circuiting the Petersen coils.

Factors Affecting Arc Extinction on a Petersen-Coil System

J. R. EATON
MEMBER AIEE

I. Introduction

THE effectiveness of the Petersen coil in extinguishing line-to-ground arcs on a transmission system is ordinarily attributed to the fact that the current in the arc is kept at a low value. Another factor of perhaps greater importance is that characteristic of the Petersen-coil system which results in a very low rate of rise of recovery voltage across the arc terminals. Although this characteristic has long been recognized,[1,2] the engineering literature would seem to indicate that its importance has not been thoroughly considered. This paper calls attention to the importance of the rate of rise of recovery voltage, presents the circuit theory pertaining to the voltage recovery rate, points out some practical aspects of the Petersen-coil system design, and compares the theory with published records of operation. It is hoped that this analysis will lead to a better understanding of Petersen-coil systems which will permit their more effective use. With continued study of system operating records, it may become possible to predict the effectiveness of a system even before it is built.

II. A-C Arc Characteristics

The characteristics of a-c arcs have been studied very extensively by many investigators, particularly with reference to oil-circuit-breaker operation. As many articles have been written on this subject,[3-6] only those salient points having a direct bearing on Petersen-coil system performance may be mentioned here. Consideration will be given only to unconfined arcs in air, as this is the type ordinarily dealt with on Petersen-coil systems.

The extinction of an a-c arc is almost entirely dependent on certain rapid changes which occur in a short interval of time near the instant of zero current. Previous to the instant of current zero, electrons are emitted in great numbers from a small area on the cathode (known as the cathode spot) in which the current density is approximately 4,000 amperes per square centimeter. This emission is due to the high potential gradient set up by space charges in the arc stream which result in a drop of 20–30 volts

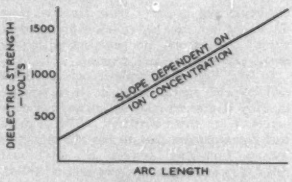

Figure 1. Dielectric strength of arc following current zero

(known as the cathode fall of potential) across a very thin layer (10^{-4} centimeters) at the cathode. The remainder of the arc stream is known as the positive column and is a highly ionized region of approximately equal numbers of electrons and positive ions. The total voltage across the positive column is dependent on its length, being approximately 20 root-mean-square volts per centimeter.

When, due to its cyclic variation, the voltage between the arc electrodes passes through zero, no potential is available in the arc column to move ions toward the electrodes. Consequently arc current and arc voltage pass through zero simultaneously regardless of whether the circuit is predominantly resistive, inductive, or capacitive.

When at a later instant, voltage of reversed polarity appears on the electrodes, the first movement of charges in the discharge space has characteristics quite different from those of the arc. The ions remaining from the previous period of conduction immediately start moving to their respective attracting electrode. However, as no cathode spot exists on the electrode that is now negative, there is at first no copious supply of electrons. The current density is low and the discharge is spread over a considerable area of the cathode. The total current is a very small fraction of the current value which would be noted in an arc. If before the air becomes deionized (from causes to be discussed later) the voltage between electrodes is raised sufficiently to cause a drop in the region of the cathode of 250 volts, a glow discharge will be established. This is a self-maintaining discharge in which large numbers of electrons and positive ions may be generated in the cathode layer. Once the glow discharge is established, the movement of the ions will set up space charges, and the potential gradient at the cathode will increase rapidly, soon resulting in the formation of a cathode spot on the negative terminal. The discharge then becomes an arc. The cathode fall of potential will again be about 20–30 volts while current density will be in excess of 10^3 amperes per square centimeter.

The voltage at which the glow discharge is established is spoken of as the breakdown strength or dielectric strength of the discharge path. This voltage is the sum of two voltages: the 250 volts required at the cathode for the establishment of the glow discharge plus the voltage which must be impressed across the region of the positive column in order to establish this 250 volts at the cathode. The voltage required across the region of the positive column is found to be approximately proportional to the column

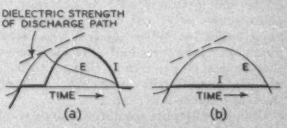

Figure 2. Circuit conditions following the instant of current zero

(a) Arc restriking
(b) Fails to restrike

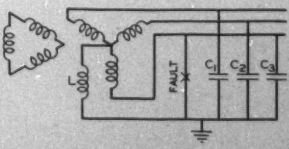

Figure 3. Petersen-coil-system circuit diagram

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1. For all numbered references, see list at end of paper.

length, the voltage per unit length increasing with decreasing ion density in the region. The dielectric strength of the ionized path is then about as shown in figure 1. Until this voltage is reached, space charges cannot be sufficiently intense to form a cathode spot necessary for the high current of the arc discharge. If following current zero, the voltage applied between electrodes does not exceed the dielectric strength of the path, the arc will not reignite and the path will soon become totally nonconducting. The fault will be cleared.

At all times the path of the discharge is losing ions by the action of the various deionizing agents present. In an oil circuit breaker these deionizing agents are very effective as the arc stream is in close contact with oil and barrier, where turbulence and surface recombination may be very important. In free air the loss of ionization is much slower and is probably due principally to volume recombination and heat loss to the surrounding air. The action of the deionizing agents over the entire cycle must be balanced by the ionizing agents which of course are most active during the conduction period of the cycle. During the period immediately following current zero, ion concentration decreases very rapidly as relatively no ionizing agents are in operation, whereas the deionizing agents are always in effect. This loss of ionization in the arc path results in an increase in the voltage required to establish the condition of the glow discharge. In other words the path gains dielectric strength with time. Circuit conditions following the instant of current zero are shown in an exaggerated form in figure 2.

As shown in figure 2, the arc path becomes almost totally nonconducting for a short period following each current zero. That is, the fault circuit is opened momentarily. In order that the arc should be reformed following current zero, the recovery voltage must at some instant exceed the dielectric strength. Obviously a low rate of rise of recovery voltage is favorable to arc extinction. The rate of rise of recovery voltage following current zero is determined by the transient characteristics of the electrical network.

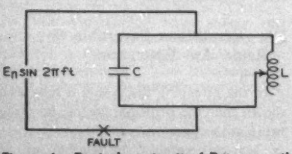

Figure 4. Equivalent circuit of Petersen-coil system (no losses)

III. System Characteristics

The essential parts of a Petersen-coil system (first approximation) are shown diagrammatically in figure 3. The current through the fault is the vector sum of the current in the capacitances C_1 and C_2 and in the inductance L. By making the inductance of suitable size, the inductive current may be made equal to the capacitive current, with the result that the net fault current is zero. The ground-fault circuit for this network (neglecting losses) is as shown in figure 4, in which C is the sum of C_1, C_2, and C_3, and E_n is the line-to-neutral voltage. With the inductance L adjusted to the correct value such that

$$2\pi fL = \frac{1}{2\pi fC}$$

no current will flow through the fault after conditions have once become stable.

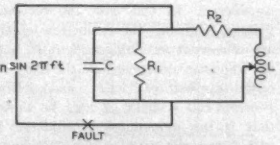

Figure 5. Equivalent circuit of Petersen-coil system (losses considered)

Under this condition the circuit through the fault may be opened without any effect on the circuit behavior. Even with the circuit open, current will continue to oscillate between the capacitance and the inductance at a frequency f, equal to that of E_n. With continued oscillation (zero losses), no voltage will appear across the arc terminals. That is, the rate of rise of recovery voltage is zero, and there is no tendency for an arc to be re-established at the point of fault.

A diagram representing actual conditions more accurately is shown in figure 5. Leakage across insulators, corona loss, etc., are represented by the resistance R_1. Conductor resistance loss and loss in the Petersen coil are represented by R_2. For the purpose of analysis, these losses may all be combined into one resistance and the circuit represented, with a slight change in the value of the inductance, as shown in figure 6. Because of its convenience this circuit will be used in the subsequent discussion.

The root-mean-square value of current in the arc is no longer zero but has some value determined by the magnitude of the system losses. If the circuit through the fault is opened, current will continue to oscillate between the inductance and

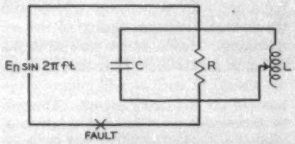

Figure 6. Simplified equivalent circuit of Petersen-coil system (losses considered)

the capacitance, but this oscillation will die down in a finite length of time as the stored energy is absorbed by the resistance R. This transient decrease of amplitude of the oscillation in the RLC branch gives rise to a voltage between the arc terminals, which tends to re-establish the fault.

In section II it was pointed out that following each voltage reversal, the current in an arc remains at substantially zero value for that short length of time required for the voltage between the electrodes to reach a value in excess of the dielectric strength of the discharge path. Hence in the Petersen-coil circuit, each time the current passes through zero, a transient is started in the RLC branch which results in an exponential decrease of the amplitude of the oscillatory voltage appearing on the capacitor. A voltage equal to the difference between the instantaneous value of neutral voltage and the instantaneous value of the capacitor voltage appears across the terminals of the fault, and tends to re-establish the arc. In a circuit such as is shown in figure 6, the current through the fault passes through zero at the instant that the voltage on the capacitor is zero. Until the arc restrikes, the voltage of the capacitor is[6] for the simplified case, figure 6,

$$e_c = E_n \epsilon^{-t/(2RC)} \sin 2\pi ft \qquad (1)$$

The recovery voltage across the fault terminals tending to cause the arc to restrike is

$$e_r = [E_n \sin 2\pi ft] - [E_n \epsilon^{-t/(2RC)} \sin 2\pi ft]$$
$$= E_n[1 - \epsilon^{-t/(2RC)}] \sin 2\pi ft \qquad (2)$$

as is illustrated in figure 7.

The rate of rise of the *amplitude* of recovery voltage is

$$\frac{dE_r}{dt} = \frac{1}{2RC} E_n \epsilon^{-t/(2RC)} \qquad (3)$$

which has an initial value ($t = 0$) of

$$\frac{dE_{r0}}{dt} = \frac{1}{2RC} E_n \qquad (4)$$

Obviously, the greater the loss in the resonant circuit (as indicated by a low value of R), the faster is the initial rise of the amplitude of recovery voltage and the greater is the possibility of the arc restriking. Hence, where possible in the design of a Petersen-coil system, the layout should be such as will minimize the losses in the oscillatory branch. This will be discussed in more detail in a later section.

Next, consider the recovery voltage conditions in a simplified Petersen-coil system (no losses considered) in which the coil current does not exactly balance out the capacitance current. That is, the system is not in tune, or

$$\frac{1}{2\pi fC} \neq 2\pi fL_1$$

Referring to figure 4, it may be observed that (considering zero loss) the current through the fault is either inductive or capacitive, depending on whether the coil inductance is less or greater than the "in tune" value. If the circuit is opened at the fault, current will continue to oscillate between the capacitance and the inductance, but the frequency of this oscillation is different from that of the power supply E_n. The oscillatory frequency will be

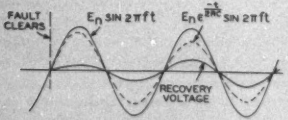

Figure 7. Recovery voltage across arc terminals, Petersen coil in tune (losses considered)

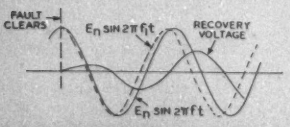

Figure 8. Recovery voltage across arc terminals, Petersen coil inductance less than "in tune" value (no losses considered)

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C}}$$

If the fault circuit is opened at the instant of zero current (which now occurs at the instant of maximum voltage on the capacitor) and no losses in the oscillatory circuit are considered, the transient voltage on the capacitor will be

$$e_c' = E_n \cos 2\pi f_1 t$$

and the recovery voltage across the fault terminals will be

$$e_r = E_n (\cos 2\pi ft - \cos 2\pi f_1 t)$$

The circuit conditions for this case are shown diagrammatically in figure 8. With this type of circuit, if f and f_1 are not greatly different, the initial rate of rise of recovery voltage is quite low, in fact much lower than would be observed on a circuit of the types shown in figure 9 in which the voltage E_n and the fault current I are of corresponding value. This explanation undoubtedly accounts for the fact that inductive or capacitive arcs of considerable current value may be extinguished on a Petersen-coil system whereas arcs of similar current magnitude on other types of circuits (for instance, on an isolated-neutral system) might be very stubborn.

As in the case of the "in tune" condition, the "out of tune" condition is more accurately represented by figure 6 in which losses in the oscillatory circuit are considered. In this case the recovery voltage following the extinction of the arc at current zero is dependent on both the frequency difference and the damping of the transient oscillation. In practical Petersen-coil systems, it may be shown that if the inductance is adjusted to within ten per cent of the "in tune" value the initial rate of rise of the amplitude of recovery voltage is principally governed by the exponential decrease of the transient oscillation. Hence in any correctly adjusted Petersen-coil system it is desirable to minimize the losses in the oscillatory circuit.

If the arc occasioned by a line-to-ground fault is stretched out (as by the wind) before extinction, a considerable voltage may be present across the arc column. Because this voltage is usually nonsinusoidal, a rigorous treatment of the effect of this arc voltage on the circuit behavior becomes quite difficult. However, the conditions may be represented at least approximately by figure 10, in which R' represents the arc. The recovery voltage of this circuit when tuned to resonance is

$$e_r = E_n \sin 2\pi ft \left[1 - \frac{R}{R' + R} e^{-t/(2RC)}\right]$$

Again it is apparent that the amplitude of recovery voltage (particularly for the in-tune condition) is closely associated with the losses in the resonant circuit and decreases with decreasing losses.

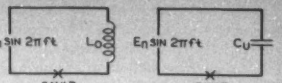

Figure 9. Circuits with steady-state characteristics equivalent to that of a Petersen-coil system which is not correctly compensated

(a) Overcompensated
(b) Undercompensated

As pointed out in section II, the root-mean-square voltage across a stable arc in free air is about 20 volts per centimeter (plus 10–20 volts cathode fall) over a considerable range of current magnitude. This voltage apparently is necessary in order to maintain the positive column, even in the presence of a cathode spot. If the arc length is increased by the wind,[7] an increasing voltage must be applied to the arc terminals to maintain the positive column. This might be approximated in figure 10 by a steadily increasing value of R'. Consideration of this circuit will show that it is impossible to increase the voltage across R' at a rate greater than that called for by equation 2. Hence arc extinction may occur if the voltage required by the positive column increases faster than the voltage which the circuit can deliver.

From the above discussion, it follows that arc extinction may result from two causes: (1) Following current zero, the recovery voltage across the arc terminals fails to reach a value equal to the dielectric strength of the arc path; (2) the arc length is increased by the wind (or otherwise) at such a rate that the voltage required to maintain the positive column of the arc increases at a rate greater than that which can be supplied by the circuit. Actually arc extinction in the Petersen-coil system probably results from a combination of both causes.

IV. Conditions Favorable to Rapid Arc Extinction

In the foregoing discussion it has been shown that the principal factors favoring rapid arc extinction are:

1. The capacitance current should be closely balanced by the Petersen-coil current. The current in the arc is then a minimum as far as reactive components are concerned, and the frequency of the resonant circuit is that of the power system.

2. The losses in the resonant circuit should be made as small as possible by proper design (to be discussed later). The in-phase component of the current in the arc will then be a minimum.

3. The damping of the oscillation in the

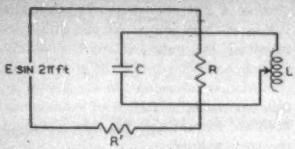

Figure 10. Approximate equivalent of Petersen-coil system, arc resistance considered

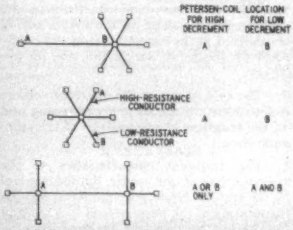

Figure 11. System arrangements in which coil location will affect rate of recovery voltage rise

resonant circuit should be low, thereby minimizing the rate of rise of recovery voltage.

4. The arc length should be as long as possible, and the gap across insulators or arcing horns should be so arranged that the arc length may be readily increased by air currents.

V. Control of Factors Which Govern Arc Extinction

1. Previous articles on Petersen-coil systems have discussed at considerable length the necessity and methods for the accurate control of the tuning of the Petersen coil at all times. While accurate tuning of the coil is probably the most important factor of all, the previous treatments of the subject make further discussion here unnecessary.

2. The control of the resonant circuit losses is a subject which has received practically no treatment in previous discussions. Within certain limits, it may be minimized by proper attention to this circuit. Champe and Von Voigtlander[8] have shown the method for setting up the zero-sequence circuits for a Petersen-coil system of any circuit arrangement. This zero-sequence circuit is of course the resonant circuit whose behavior under transient conditions has such a great effect on the rate of rise of recovery voltage. In setting up this circuit for the purpose of studying the rate of decay of the transient oscillation, it is necessary to include the resistive components of the circuit impedances, and where appreciable, the conductance due to corona losses and insulator leakage. An analysis of the transient characteristics of the equivalent circuit (figure 6) will then clearly demonstrate that the exponent of the damping factor,

$$-\frac{t}{2RC}$$

will in some cases be greatly affected by Petersen-coil location alone. Examples of typical system arrangements in which coil location will be of considerable importance are shown in figure 11.

In general, it may be stated that for best operation, each Petersen coil should be located as near as possible to the capacitance which it compensates, and the connection between the coil and the capacitance should be made through a line having low conductor loss. While practical considerations may in many cases dictate the location of the Petersen coils it must be borne in mind that arc extinction will be much more certain if the coils are so located that the resonant circuit losses are as low as possible. This of course is in direct contradiction to the claims of some writers who have stated that the choice of the coil location is merely a matter of convenience. Fortunately, the desire to locate the coils at points where there would be the least chance of disconnection by switching operations, has in most cases resulted in the installation of the coils at the capacitance centers.

It is of course obvious that the coils themselves and the star-delta transformers connecting the coils to the system should be designed for low loss, inasmuch as they form part of the resonant circuit.

3. The rate of decay of the oscillation in the resonant circuit will in general be determined by the circuit constants and the Petersen-coil locations. Artificial control of this rate of decay may, theoretically at least, be accomplished by the addition of low-loss capacitors across the terminals of the Petersen coil as shown in figure 12. The coil must then be tuned to balance the equivalent capacitance

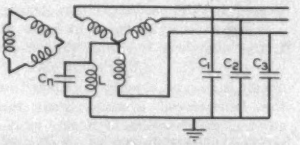

Figure 12. Capacitor added across Petersen-coil terminals to increase stored energy in resonant circuit

$$C_e = C_n + C_1 + C_2 + C_3$$

Ignoring the loss in the capacitance C_n and the possible increase of loss in the Petersen coil itself, the exponent of the damping factor $-t/(2RC)$ (of the simplified circuit, figure 6) will decrease inversely as the equivalent capacitance C_e is increased. To reduce the exponent to 50 per cent of its original value would require the installation of approximately three microfarads per 100 miles of overhead line. The installation of capacitors for this purpose might be quite practicable, particularly on low-voltage circuits. Their use might be well justified on circuits having limited physical clearance on which ground fault arcs must be cleared quickly before they have opportunity to spread to the other conductors.

4. The length of the arc path, as has been shown, affects to a great extent the extinction characteristics. In fact it can be stated that the extinction of arcs on a given system probably occurs when the arc is increased by the wind or otherwise to some fairly definite length dependent on the recovery characteristics of the system. It would be expected that extinction would be much more likely on an overinsulated system than on an underinsulated system because of the difference in the striking distance across insulators. On systems already in operation, there is probably but little chance of improving the extinction characteristics by control of the arc length without major line changes. However, on new construction or in rebuilding, attention should be given to provide a design in which the arc may be stretched out by the wind with a minimum chance of producing line-to-line faults.

VI. Comparison of Theory With Operating Experience

The story of the recovery voltage on a Petersen-coil system is shown quite strikingly at the end of every oscillographic record of a line-to-ground fault.[2,9,10] As predicted by theory, normal conditions are not restored at the instant the fault is cleared, but are brought about through a transient. The exponential character of this transient is effectively demonstrated by plotting on semilogarithmic paper the oscillograph deflection of successive crests of Petersen-coil

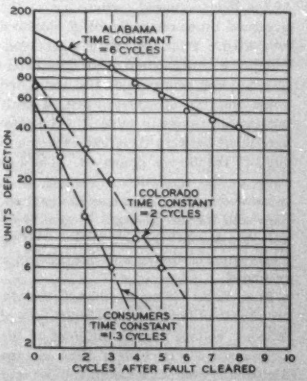

Figure 13. Damping of the oscillation at the end of a line-to-ground fault

current or neutral voltage. Figure 13 shows the straight-line characteristics of the logarithmic plot of Petersen-coil current from published data obtained from the Consumers Power Company* and the Alabama Power Company,† and a

* Figure 12 of reference 9.

† Figure 29 of reference 2.

similar plot of the displacement from normal of the line-to-ground voltage from the Public Service Company of Colorado.*

Considerable information relative to the characteristics of the various systems may be computed from figure 13. The time constant of an exponentially decreasing function is defined as the time required for that function to diminish to $1/\epsilon$ or

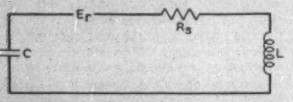

Figure 14. Resonant circuit in which residual voltage operates

37 per cent of its original value. For the circuit of figure 6, the time constant may be shown to be

$$\text{time constant} = 2RC \qquad (5)$$

The time constants for the three systems have been determined from figure 13, and are shown in table I. Dividing the system neutral voltage by the time constant gives the initial rate of rise of the amplitude of recovery voltage (equation 4). It may be noted that this initial rate of rise is quite different for the three systems investigated.

From equation 5 and the known values of the line-to-ground capacitance of the overhead lines, the value of R has been computed. From this, the in-phase component of fault current is at once determined. For comparison, the computed value and the measured value of fault current are shown in table I. The close agreement between these values seems to support the theory presented. The low value of the equivalent resistance R as calculated for the Consumers Power Company and for the Colorado system probably was due to excessive losses resulting from corona occurring with one conductor grounded.

From table I it may be noted that the initial rate of increase of the amplitude of recovery voltage is quite different on the Consumers Power system than on the Alabama Power system (3,700 kv per second as compared to 255 kv per second). From theory it would seem that for similar arc extinction characteristics, arc length and the rate of voltage recovery are associated in a relation of approximately linear character. Even when considering the difference in insulator clearance provided at 140 kv as compared to that at 44 kv, it appears that the extinction characteristics of the two systems might be quite different on the basis of voltage recovery alone. In addition the Alabama system had the advantage of low arc current, 2.5 amperes, as compared to 40 to 50 amperes on the Consumers Power Company system. It is of interest to note that on the Consumers Power system, arcs established by lightning frequently continued for several seconds even under the action of the severe air currents which ordinarily accompany storms. On the Alabama system, even during staged tests, the period of the arc was very short. In actual operation,[11] numerous disturbances were reported which were too short in duration to give complete fault records. It is possible that these were faults which were extinguished at the first current zero.

The circuit-recovery-voltage characteristics of a Petersen-coil system may be determined with a considerable degree of accuracy from the tuning curve obtained with no grounds on the system, provided however that corona is not excessive under the condition of one conductor grounded. Tuning curves obtained from normal operation require that the unbalance of transpositions result in a slight residual voltage in the system. It may be considered that this residual voltage operates in a series circuit as shown in figure 14. If the inductance is varied, the current will vary reaching a maximum when the circuit is in tune, exactly as is noted on the Petersen-coil system. From this curve alone, the value of R may be determined by straightforward calculations. Considering the transient characteristics of this circuit, it may be shown that the time constant is $2L/R$, from which the value of α and the other factors shown in table I may be determined. Using the tuning curve of the Colorado system, the time constant is calculated to be 0.0536, the initial rate of rise of the amplitude of recovery voltage (system in tune) to be 1,150 kv per second, and the fault current to be 12.5 amperes. Here again we may observe a fair comparison between the values of these important quantities determined by quite different methods. Corona occurring during the ground-fault condition which cannot be considered by this approach, would tend to increase both arc current and the rate of rise of recovery voltage.

VII. Conclusions

1. The extinction of arcs on Petersen-coil systems is dependent on the magnitude of the current in the arc, the rate of rise of the recovery voltage across the arc, and the arc length.

2. The rate of rise of the recovery voltage is dependent on the accuracy of tuning and on the transient characteristics of the resonant circuit.

3. The transient characteristics of the resonant circuit are under limited control by the system layout, particularly as regards the location of the Petersen coil. A method for altering the transient characteristics by the use of capacitors is suggested.

4. The magnitude of the uncompensated fault current and the rate of increase of the amplitude of the recovery voltage may be accurately calculated from the known line constants.

5. Satisfactory operation has been reported from Petersen-coil systems having considerably different rates of rise of recovery voltage, consideration being given to differences in arc length for systems operating at different voltages. A further study of system operation may establish the limits in which operation will be successful.

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4. Extinction of a Long A-C Arc, J. Slepian. AIEE Transactions, volume 49, 1930, page 421.

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6. Electric Discharges Waves and Impulse

Table I. Characteristics of Three Petersen-Coil Systems

	Consumers Power Company	Public Service Company of Colorado	Alabama Power Company
Time constant: Cycles	1.3	2.0	6.0
Seconds	0.022	0.033	0.10
1/(time constant) (α)	45	30	10
System voltage, kilovolts	140	100	44
Neutral voltage, kilovolts	81	58	25.5
Initial rate of increase of amplitude of recovery voltage (αE_m), kilovolts per second	3,700	1,740	255
Voltage across arc terminals at the end of one-fourth cycle, kilovolts	13.9	6.8	1.04
Capacitance of resonant circuit (from published data), microfarads	6.80	5.65	2.7
$R = 1/(2\alpha C)$ ohms	1,620	2,930	18,500
In-phase arc current: Calculated E_m/R	50	19.5	1.4
Measured	40–50	22	2.5

* Figure 14 of reference 10.

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Discussion

E. M. Hunter (General Electric Company, Schenectady, N. Y.): In connection with the theory of the arc-quenching properties of the Petersen coil, Mr. Eaton shows that the time constant of the system recovery voltage can be used as a criterion of the performance to be expected. This time constant is equal to twice the product of the resistance and the capacitance in the zero-sequence circuit of the system, and to improve arc extinguishing, this time constant should be lengthened. Mr. Eaton suggests that this may be done by decreasing the losses in the circuit. A low-loss circuit will improve he Petersen-coil performance with regard to quenching ground faults, but may complicate matters during normal operation. On every three-phase system there is some slight unbalance in the three-phase voltages to ground so that there is some residual voltage between the neutrals of the system and ground. In normal operation the Petersen-coil reactance and the zero-sequence capacity reactance of the system form a series resonant circuit, and consequently, the installation of a Petersen coil in the system neutral amplifies the residual voltage. The increase in voltage at the neutral depends upon the same losses in the circuits which were previously mentioned. A low-loss circuit means a high residual voltage. To decrease this residual voltage, the system must be balanced electrostatically. On a low-loss circuit it may be a considerable problem to reduce the normal residual voltage to a level considered suitable for the system. All of this is to indicate that there are practical limits beyond which it may be undesirable to attempt to reduce the losses.

Mr. Eaton also concludes that the best results are obtained from Petersen coils when they are located as close as possible to the capacitance which they are compensating. A very practical significance of this which undoubtedly Mr. Eaton recognizes but which was not brought out in his paper is this. In protecting a given system with Petersen coils, a multiplicity of small coils properly located in the system will give a better performance than one large coil for the entire system. This principle was carried out on the Metropolitan Edison Company's application when three coils were installed. The operating experiences reported by Messrs. Rankin and Neidig, both with the system connected together and divided, justifies the larger number of coils.

The necessity of paralleling the Petersen coil with a low-loss capacitor to increase the stored energy in the circuit, as commented on in Mr. Eaton's paper, on every installation is questionable, but undoubtedly on some circuits where the losses of the circuit may be high due to corona or other causes, this additional shunting capacitor might be of some benefit. This capacitance might also be located on the high-voltage terminals of the transformer in the neutral of which the Petersen coil was located. In this location the capacitors would be so proportioned that they would balance the system electrostatically and thus overcome the previously mentioned objection of the low-loss circuit.

J. R. North and **F. Von Voigtlander** (both of Commonwealth and Southern Corporation, Jackson, Mich.): Mr. Eaton is to be complimented on his very clear exposition of the phenomena involved in the extinction of an unconfined a-c arc in air and for directing attention to the importance of rates of voltage recovery rise and their bearing on successful Petersen-coil operation, particularly on systems where appreciable magnitudes of in-phase components of fault current are involved.

The author suggests shunting the Petersen coil by low-loss capacitors to control the damping factor of the Petersen-coil system. It would appear that the size of such capacitors would be quite large as compared to the capacitance of the lines and might necessitate a considerable increase in the size of the Petersen coil necessary to balance the system capacitance together with this added capacitance.

From time to time tests have been considered to determine the upper limit of magnitude of the in-phase component of ground-fault current that can be successfully extinguished by the use of Petersen coils on various systems. The author points out clearly that not only is the magnitude of such currents an important factor, but the differences in recovery rates of various systems would probably widely affect the maximum currents that could be successfully handled.

Referring to conclusion number 5, it should not be overlooked that there are a number of other factors besides recovery voltage which must also be given careful consideration in analyzing the possible application or performance of Petersen coils on a given system. These include such factors as the magnitude of dynamic voltages experienced on nonfaulted phases, system operating voltage with respect to the corona limit, system network complexity, and required isolation of permanent faults.

A. U. Welch (General Electric Company, Pittsfield, Mass.): Mr. Eaton's statement that "Peterson coils and associated grounding transformers should be designed for low loss" might give the impression that special designs with abnormally low loss would improve the performance by lowering the voltage recovery rate.

However, the I^2R loss in a transmission line and its ground return when supplying charging current to ground is of the same order of magnitude and often higher than the loss in a normal-design Petersen coil. Furthermore, particularly in high-voltage systems, the corona loss with a ground fault is generally much higher than the resistance loss in lines, ground, and Petersen coil. Therefore, reducing the loss in the Petersen coil reduces the total loss only slightly and has negligible effect upon recovery voltage.

J. R. Eaton: Mr. Welch points out that it may be impracticable to reduce the losses in the resonant circuit beyond a certain point. Further attempts to decrease this loss may result in an increased cost entirely out of proportion to the advantage obtained. As mentioned by Mr. Hunter, a reduction of these losses will result in an increase in the residual voltage on the system during normal operating conditions. Hence we find here, as in almost all engineering problems, that we must give consideration to all factors involved and choose as our solution that value which will give the best over-all operation.

Mr. Hunter points out that if capacitors were used to increase the stored energy in the resonant circuit, they might be located at the line terminals of the grounding transformer bank. Although this connection would be satisfactory from the standpoint of system-recovery-voltage characteristics, it may be observed that capacitors so connected would be at all times subjected to full line-to-ground potential. If connected to the system neutral, as suggested in the paper, the capacitors would be subjected to line-to-neutral voltage only during the fault period.

The comments of Mr. North and Mr. Von Voigtlander are of importance in that they call attention to the necessity of a broad consideration of the problem before justifying an installation of Petersen coils on a system. The present paper treats only the factors affecting arc extinction. This of course is only one of the many problems which must be considered in Petersen-coil application.

Induced Current in Parallel Circuits and Its Effect Upon Relays

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MUTUAL INDUCTION is very much like friction in that it is a great blessing under certain conditions and an unmitigated nuisance under others. If it were not for mutual induction there would be no a-c systems as we know them today because there would be no transformers. It is apparent, therefore, that mutual induction is the basis of an entire industry that could not exist without it. On the other hand it has been the bane of the communication industry where induction between circuits is highly undesirable. There is a story told about one of the early long-distance open-wire telephone circuits having several parallel lines in which the experimenter at one end spoke to the man at the other end and asked "Do you hear me?" The reply was, "Perfectly." The first man then asked the second, "Which line am I on?" and after a moment's hesitation the second replied, "All of them." These two illustrations show that mutual induction may be either a blessing or a curse depending upon the circumstances under which it exists.

In three-phase power systems, mutual induction is usually negligible for one or both of the following reasons. In a great majority of installations, the spacing between conductors is so small in comparison with the spacing between circuits that comparatively few of the lines of flux produced by one circuit link the other. The second reason is the presence of transpositions which are commonly employed to balance circuits and to minimize unbalances between circuits caused by mutual induction. If each conductor of each three-phase circuit occupies each of its nine possible positions with respect to each conductor of any other adjacent three-phase circuit for one-ninth of its length, the net effect of one balanced three-phase circuit upon another will be zero. Transpositions of transmission line conductors are normally worked out to approach this ideal quite closely.

The flux field generated by zero-sequence (or ground) current, that is, current flowing out over one or more conductors and returning through the earth, is quite different from that existing in a balanced three-phase system. In this case the circuit spacing of two parallel circuits on the same towers or the same right-of-way may be small in comparison with the conductor spacing since the conductors are the wires of the transmission line and the path of the current in the earth. Furthermore, no transpositions are possible. As a result the mutual inductance between circuits carrying zero-sequence current may vary from zero for widely separated circuits to perhaps 75 per cent of the self-inductance in the case of a double-circuit tower line. A mutual inductance of the order of 50 per cent or greater is far from negligible in determining the distribution of flow of current in the parallel circuits, as will be shown.

To most people resistance and self-inductance are readily understandable terms, but mutual inductance being less commonly encountered seems to be a little more difficult to comprehend. Perhaps the explanation which made its nature clear to the author will be helpful to others, that is, an exact definition of what mutual inductance is. Mutual inductance is the flux linkage with one circuit per ampere in another. Let us examine this statement as applied to a transmission line conductor and see what it says. Everyone knows that self-inductance is the flux linkage per ampere in the circuit itself. In other words, it is the total number of flux lines surrounding the current of one ampere flowing in the circuit. Returning now to mutual inductance, it will be seen that it is merely the number of flux lines around a conductor that results from a flow of one ampere in some other conductor. These statements apply to straight cylindrical conductors, such as transmission lines. When the conductor is in the form of a coil, such as in a transformer, the flux linkage is the sum of all of the flux lines times all of the turns through which they go, when a current of one ampere is flowing.

The transition from mutual inductance to mutual reactance is now very easy to see because reactance is merely the time rate of change of flux linkages per ampere. In other words having established a mutual inductance it is merely necessary to multiply it by $2\pi f$ to obtain the mutual reactance.

There is also present some mutual resistance because the return circuit for both the inducing and the induced currents is in the earth which has some resistance. Accordingly, two adjacent circuits have a mutual impedance containing both a resistance and a reactance term. The formula for calculating the mutual zero-sequence impedance between transmission circuits carrying zero-sequence current will be found in any standard reference book on transmission line calculation[1] and is

$$Z_{mo} = 0.00477f + j0.01397f \log_{10} \frac{D_e}{\text{G.M.D.}}$$

ohms per mile per phase

where f is the frequency, D_e is the distance between the equivalent conductor and its image, and G.M.D. is the N^2 root of the product of the N^2 possible distances between the N conductors of each of the two circuits. For three-phase circuits this becomes the ninth root of the product of nine possible distances.

Where there are many circuits to be calculated, much time may be saved by referring to figures 77 and 82 of the book "Symmetrical Components" by C. M. Wagner and R. D. Evans. From these figures the equivalent depth to the image and the mutual zero-sequence reactance may be obtained directly, and the only computation necessary is the derivation of the geometric mean distance between the conductors designated as G.M.D.

Whenever two circuits having mutual zero-sequence reactance are electrically connected at one or both ends, an equivalent circuit may be drawn showing both the self and mutual zero-sequence impedances,[2] and this will be found most convenient in setting up the impedance diagram for the purpose of calculating the flow of zero-sequence current. Where the lines are bussed at both ends and a fault exists along the length of one of the circuits, two equivalent impedances may be set up, each representing the network in one direction from the point of fault and the two equivalent networks connected together and reduced by the well-known wye-delta method or set up on a calculating table. See figure 1*b*.

The effect of mutual reactance between circuits is to cause circulating current, or a

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1. For all numbered references, see list at end of paper.

redistribution of the ground fault current as calculated without the effect of mutual zero-sequence impedance. The first evidence of this probably manifested itself in connection with directional ground relays where an inexplicable lack of selectivity appeared. Some years ago, before the methods of calculating the flow of zero-sequence current were as well known as they now are, cases would frequently arise in which there was an apparent loss of selectivity between directional ground-current relays that, according to calculations, should have had plenty of time interval between them. In the light of subsequent knowledge it is easy to understand how the time interval became too small to retain selective action.

As the use of directional ground-current relays on parallel circuits is still very common, it may be worth while to show why it is that a fault on one of the lines will

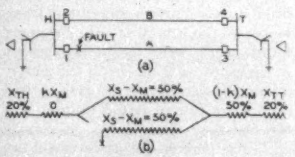

Figure 1

(*a*) One-line diagram of parallel line system

(*b*) Equivalent zero-sequence reactance diagram for ground fault after breaker number 1 opens

X_{TH}—Zero-sequence reactance external to *H*
X_{TT}—Zero-sequence reactance external to *T*
X_S—Zero-sequence reactance of one line
X_M—Mutual zero-sequence reactance between lines
k—Relative distance from *H* to fault

occasionally trip three breakers. For the sake of simplicity assume that the zero-sequence impedance external to the two parallel circuits of figure 1*a* is the same at both ends and that a fault occurs at *X* in line *A* near *H*. If the line zero-sequence impedance is fairly high in comparison with that of the grounding transformers at the ends, a large proportion of the zero-sequence current will initially flow through the neutral of the grounding transformer at *H* and the relays of circuit breaker 1. In the meantime current will flow in a tripping direction and possibly of tripping magnitude through breakers 3 and 4, but presumably breaker 1 will open before either of these operate or no kind of selectivity would be obtained. After breaker 1 has opened, it might appear that the major part of the ground current would now return through the neutrals of the transformers at *T* since these are apparently nearer the fault than those at *H*. As a matter of fact, if the mutual zero-sequence impedance between lines is one-half or a greater proportion of the self-impedance of one line, then one-half or more of the ground current will return to the neutrals of the transformers at *H*. This is true regardless of the length of the circuits providing only that the mutual reactance is one-half or more of the self-reactance, and also assuming equal impedance of the grounding transformers. See figure 1*b*. As a result of the opening of breaker 1, breaker 3 relay then gets more current than breaker 2 relay, but by no means so much more as might have been expected, and accordingly, breaker 2 relay, if set without consideration of the effect of mutual impedance, may succeed in tripping before breaker 3 has cleared the short circuit.

Mutual zero-sequence reactance is no respecter of persons and is not concerned with whether the two circuits involved have any electrical connection with each other or not. Its action is not confined to parallel circuits of the same voltage or even the same frequency and this has occasionally resulted in some rather mysterious behavior on the part of directional ground-current relays. Figure 2 illustrates a condition which has been known to cause operation of directional ground relays on one overhead grounded-neutral system that is paralleled by an electrically separate grounded-neutral system for a part of its length. Ground faults on the second line cause flux linkages with the first line that generate a voltage between the ends of each of the three conductors. Since both ends of every conductor of the first line are connected to ground through the wye windings of wye-delta transformers, there is a comparatively low impedance path around which these induced voltages can force a flow of current. It will be observed that at one of the transformer banks the direction of current flow is from the ground to the neutral and up through the winding and out over the transmission line while at the other transformer, the flow is reversed, being in on the line and down through the transformer to the ground. The relative direction of the current in the neutral and the current in the line is the same in both cases and is such as to cause the relays to act as if there is a flow of fault current into the line at both ends. If this is sufficient in size and duration, one or both of the directional ground relays will operate to clear a circuit which is electrically isolated by a double transformation from the faulty section.

An even more mysterious and obscure case occurred on an underground system in a city where there are 25- and 60-cycle cables in the same duct bank under the street as shown in figure 3. One of the 60-cycle cables formed a portion of a loop circuit which was protected with directional ground-current relays. On several occasions faults on the 25-cycle system that caused ground current to flow in one of the 25-cycle cables in the duct would trip 60-cycle directional ground relays. At first thought it might seem that the metallic sheaths of the cables would act to shield the conductors of one cable from the flux field around the conductors of another carrying ground current. Actually the sheaths do have some such effect, but on account of the relatively high-resistance material of which they are composed, they are not a very effective shield. Accordingly, there were enough effective flux linkages with the conductors of the 60-cycle cable to force sufficient current around the loop of which it was a part to operate the ground relays. If the system is grounded at the source only, the ground-relay torques are in the directions indicated in figure 3, and increase progressively away from the grounding point. If the system has more than one ground the current circulating in the earth would change the torques, but half of the relays in the loop tend to trip.

Where two parallel identical circuits have unequal mutual coupling with a third circuit, any ground current in the

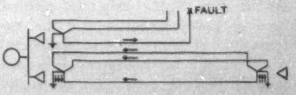

Figure 2. Flow of currents in a circuit exposed to zero-sequence induction

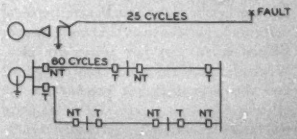

Figure 3. Flow of current in a loop exposed to zero-sequence induction

T—Tends to trip
NT—Tends not to trip

latter generates a voltage around the loop formed by the two parallel circuits. This voltage produces a circulating current which is superimposed on any ground-fault current that may be flowing in the two circuits at the moment, thus tending

to increase the current in one line and reduce it in the other. Where the lines are protected by balanced current relays in the residual circuit of the current transformers, faulty operation may result from the superposed circulating current on top of the balanced through current. The circulating current may be calculated by subtracting the mutually generated zero-sequence voltages in the exposed section and dividing it by the loop zero-sequence impedance of the two circuits.

Three or more parallel circuits on the same right-of-way necessarily have unequal mutual zero-sequence impedances so that through ground-fault current will not divide evenly between them. The middle circuit will carry less current than the others which may cause false operation of ground-current relays.

Mutual zero-sequence reactance is open to indictment on still another count. It is one of the factors that make the use of distance relays for ground protection so complicated that it becomes very nearly impracticable. If it were not for the mutual reactance between circuits, distance relaying for ground faults would be no more complicated than for phase faults, but the fact that the voltage generated between the fault and the relay location in the faulty conductor may contain a large mutual zero-sequence component makes it necessary to take into account in each relay the zero-sequence current in all parallel circuits in order to secure accurate distance measurement. It is quite apparent that where there are several circuits on the same right-of-way, the problem becomes pretty complicated if the currents in all of them have to be conducted to the relays in all the others. It is quite probable that this is the chief reason why distance ground relaying has not become very prevalent.

Although not strictly induction, there is another source of unbalanced residual currents in parallel lines that must be considered when very fast relays are used. When one circuit of a pair is carrying load and the second circuit breaker on the other is closed to parallel them, its poles will strike sequentially electrically regardless of the excellence of mechanical adjustment. There is a moment during which only one wire of the incoming line is in parallel, then a second interval when two wires are completed and finally all three are closed. For the first two intervals there is a zero-sequence current in each line. Where the system neutral is ungrounded this current flows only in the loop formed of the two lines and is equal in each and, therefore, would not tend to operate residual balanced current relays. Where there are grounded neutrals on both ends of the lines there is a true zero-sequence current flow via the grounding transformers and the earth and it is unbalanced in the two circuits.

For the condition of one pole of the breaker closed, the current may be calculated from an equivalent circuit in which the negative and zero-sequence impedances as viewed from the breaker are placed in series and inserted in the positive-sequence network as a series impedance at the breaker location. When two poles are closed the negative- and zero-sequence impedances are paralleled and connected in series with the positive-sequence network at the breaker location. From calculations like these the effect on balanced and directional ground relays may be determined.

Ground-fault currents generate voltage in any mutually coupled conductor without regard to the use to which it is put. Pilot wires used for relaying, telemetering, and similar purposes may have excessive voltages induced in them if they are in close proximity to aerial or underground power conductors carrying zero-sequence currents. The voltage is usually very small between wires but the voltage to ground may be high on all of them, thus endangering the insulation.

Mutual resistance, too, has caused insulation failures in pilot wires and equipment connected to them. The fault current returning from the earth to the neutral of a grounding transformer passes through whatever resistance there is between true earth and the station grounding system to which the transformer neutral is connected. The resultant *IR* drop displaces the station ground from true earth potential. The cases of equipment connected to the pilot wires are ordinarily grounded to the station ground and the pilot sheath is usually grounded purposely or accidentally to the earth along its length. The insulation of the equipment and the pilot wire in series is subjected to the potential between station ground and earth and is stressed in inverse ratio to the capacitances between the equipment and station ground and between the pilot wires and their sheath. In most cases the equipment capacitance is small and its insulation gets most of the voltage across it. Sometimes the reverse is true.

Having outlined some of the effects of mutually induced current, it is quite appropriate to discuss some of the methods which have or may be applied to circumvent the harmful consequences. The simplest point of attack is in the relay setting. In the first instance discussed it will often be found that once the correct distribution of residual or zero-sequence current has been determined, a change in the settings of the relays will give the desired selectivity.

In figure 2 the relay at the station where both circuits are grounded can be made to recognize the true direction of fault current by energizing its polarizing coil from the sum of the secondary currents of current transformers in all of the power transformer neutrals. The ratio of these current transformers should be in the inverse ratio of the voltage ratings of the system in whose neutral they are connected so that an equal kilovolt-amperes in each system will give equal secondary currents. The actual fault current which is doing the inducing will be greater than the induced current (in kilovolt-amperes) and hence the net current fed to the relay polarizing coil will be reversed from what it would have been had it been energized from a current transformer in the neutral of only the power transformer to which its line is connected. At the other end of the circuit this remedy is not available because the fault current itself is not present in this station. For this location there is no universally applicable remedy, but an expedient has been used that should be successful in many installations. The line-to-neutral voltages of the circuit in which the induced current flows are usually higher during the induced-current condition than they are while a ground fault exists in the line itself. This fact may be utilized through the use of three instantaneous undervoltage relay elements, the coils of which are energized from the line-to-neutral voltages and the contacts of which are all in parallel and the group in series with the directional relay whose misoperation is to be prevented.

While the author is not aware of any installation made for the special purpose of reducing mutual zero-sequence reactance between circuits, it is a fact that counterpoises and good-conducting ground wires tend to reduce the mutual zero-sequence reactance. This will be readily apparent when it is considered that the presence of these conductors brings into proximity with the inducing current, a returning ground current of opposite direction. This returning current also has a mutual coupling and since it is in the reverse direction tends to cancel out part of the voltage generated by the outgoing current in the parallel circuit conductor. If all of the ground current could be persuaded to return in a ground wire or counterpoise spaced the same distance from the circuit in which the voltage

is induced as the inducing circuit conductors, it would entirely cancel out the mutual reactance between the circuits. A perfect result is unobtainable but may be approached through the use of good conducting ground wires and counterpoises and by increasing the separation between the parallel circuits through the use of separate rather than twin circuit towers. It is not proposed by the author that this should be adopted as an economical remedy for false operation of ground relays, but is merely pointed out as another one of the advantages incident to the use of counterpoises and ground wires.

The use of conducting shields for pilot wires has been proposed since the cost is not prohibitive as it may be for power circuits. Where momentary interruptions are not harmful vacuum gaps or Thyrite resistors have been used to limit the voltage from pilot wires to ground. In other installations a higher insulation level has been provided, capable of withstanding the induced voltages. Occasionally neutralizing transformers[3] have been installed to allow station equipment to stay at station ground potential and the pilot conductors at true earth potential. Insulating transformers at the station boundary have also been employed where the quantity sent over the pilot wire is alternating current. The choice between the various remedies is one of economics for the particular installation.

Conclusion

Mutual impedance exists between adjacent circuits carrying zero-sequence or ground current. Its effect is to cause a different distribution of ground current than would have existed without it. Failing to take it into consideration has occasioned incorrect operation of ground relays, usually of the directional type. It has also caused false operation of balanced ground-current relays. Its existence makes distance ground-fault protection difficult. It also endangers the insulation of pilot wires and equipment connected to them. A number of remedial measures are available, but there is no universal, economical panacea. Each instance requires individual consideration to determine which of the several available remedies may best be utilized.

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2. Simultaneous Faults on Three-Phase Systems, Edith Clarke. AIEE Transactions, September 1931, page 936, appendix C.

3. Neutralizing Transformer to Protect Power Station Communication, E. E. George, R. E. Hosaman, L. L. Lockrow, and E. L. Schwartz. Electrical Engineering (AIEE Transactions), May 1936.

Discussion

R. P. Crippen (Ebasco Services Incorporated, New York, N. Y.): In 1931 trouble was experienced from incorrect relay operation on the 13.2-kv system of the Tennessee Public Service Company in Knoxville, Tenn.

This system was fed from a single 110/13.2-kv substation of about 30,000 kva. Six overhead 13.2-kv tie lines ran from this substation to various other substations about the city. These substations were in turn joined together by other 13.2-kv tie lines. There resulted a network of 13.2-kv circuits, most of which were not more than two or three miles long and many of which were arranged two or three to a pole line. No transpositions were used. The system was grounded through a 20-ohm resistor in the neutral of one of the 10,000-kva transformer banks at the main substation.

Tests were made and it was found that for straight ground faults induced zero-phase-sequence currents up to a maximum of 90 amperes would flow in unfaulted lines. This indicated that ground relays on the lines thus affected should have a current setting which would allow for the induced currents.

A more difficult problem arose when simultaneous ground faults occurred at different points on the system on different phases, as sometimes happened. The resultant unbalanced currents in the lines were several times as great in magnitude as the current to a single ground fault, which was limited by the 20-ohm resistor. These heavy currents circulating between the two ground faults resulted in unbalanced currents in individual circuits which were much heavier than the straight zero-phase-sequence currents to ground faults. The resultant "mix-up" from unbalanced and induced currents was bewildering.

Reasonably good operation was obtained by increasing the current setting of certain of the ground relays, by applying the directional control feature to both phase and ground directional relays at certain points, and by installing faster-acting relays at two or three points.

The case illustrates what can occur under certain conditions and what is undoubtedly occurring to a lesser degree in many instances. Fortunately effects such as this are not usually sufficient in magnitude to cause any trouble to the relay engineer.

R. E. Neidig (Metropolitan Edison Company, Reading, Pa.): Mr. Bancker's paper will be of decided interest to every relay engineer who is faced with the problem of relaying grounded-neutral systems, and while the subject is not new, I believe that it has been given too little publicity in the past.

Several years ago it was discovered that mutual induction was the cause of incorrect relaying on one section of the 110-kv system of the Metropolitan Edison Company, and it is believed that a review of that instance at this time will be interesting.

Figure 1 of this discussion shows the central section of the aforementioned 110-kv system. The circuits between South Reading and Glendon are on two-circuit steel towers, and likewise are the circuits between Glendon and Gilbert. However, the latter tower line is on the same right-of-way with the South Reading-Glendon tower line for a distance of six miles out of Glendon. There are no ground wires on either tower line.

After experiencing a few cases of instability at Gilbert plant from 110-kv faults, high-speed balanced-phase and ground relays were applied at the three stations shown, and the oil circuit breakers modernized at Gilbert and Glendon. Immediately after this modernization program was completed, it was discovered that ground faults occurring on the South Reading-Glendon circuits were, in a number of cases, causing peculiar ground-relay operations on the Glendon-Gilbert circuits. In most cases where these peculiar operations occurred, the oil circuit breaker on one circuit at Gilbert was tripped by the balanced-ground relay, and the oil circuit breaker on the other line at Glendon was tripped by its balanced-ground relay. Occasionally only the oil circuit breaker at Gilbert was tripped. Obviously, something had to be done about it.

This type of operation indicated that the residual currents in the Glendon-Gilbert circuits was becoming unbalanced for some reason, and as this condition did not exist for faults beyond Gilbert toward West Wharton, it suggested induction in the six-mile section out of Glendon as the probable cause.

Inspection showed that the maximum induced voltage in the Glendon-Gilbert circuits would occur during a ground fault on the adjacent South Reading-Glendon circuit at a point where the two tower lines left the common right-of-way. Results of calculations made under these conditions are given in figure 1, showing that the loop current

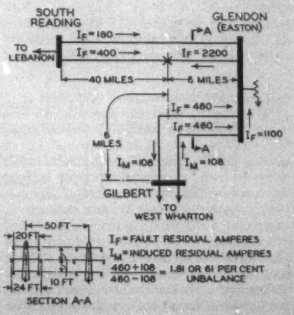

Figure 1. Section of 110-kv system of Metropolitan Edison Company affected by induced current and results of calculations for typical case

induced in the Glendon-Gilbert circuits caused as much as 61 per cent unbalance in their balanced-ground relays, which was far more than sufficient to cause operation.

There were two apparent means for

eliminating the peculiar operations caused by this condition, (1) reducing the sensitivity of the balanced ground relays, requiring either changes in the relay or additional auxiliary relays, or (2) removing the balanced-ground relays from service. While the latter means of correction may seem more or less rash, it must be pointed out that the current obtained in the faulted phase during a ground fault at any location on the Glendon-Gilbert circuits is very high, and of sufficient magnitude to operate the balanced-phase relays. Inspection of operating records showed that in practically no case did a balanced-phase relay fail to operate together with the balanced-ground relay for ground faults on these circuits. This fact, determined quickly and easily, led to the temporary disconnection of the balanced-ground relays, although thus far they have not been restored to service. Each circuit, however, is still equipped with back-up ground-relay protection.

It will be interesting to note that ground faults on the Glendon-Gilbert circuits produced no apparent peculiar operations of the South Reading-Glendon circuits, due, no doubt, to the appreciably higher loop zero-sequence impedance of these circuits. The balanced-ground relays on these circuits are still in operation, although it was necessary to reduce the sensitivity of them due to the difficulty encountered from sequential operation of oil-circuit-breaker poles, a source of trouble also referred to in Mr. Bancker's paper.

Wm. E. Marter (nonmember; Duquesne Light Company, Pittsburgh, Pa.): Mr. Bancker has presented a very interesting paper on the effect of induced current on relaying. This problem has been encountered in many places on the Duquesne Light Company system and in one instance has been successfully solved by a scheme installed during 1932, and which to my knowledge has not been published.

Figure 2 of this discussion shows the arrangement of 66-kv lines on which trouble was encountered. The lines were on double-circuit towers over separate right-of-ways with one Pine Creek line and

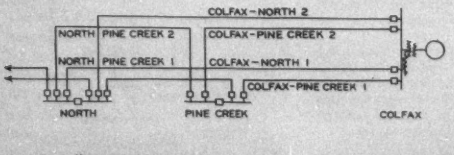

Figure 2

one North line on each tower line. A fault near North substation on a North-Colfax line caused a circulation of induced current in the pair of lines between North and Pine Creek and between Pine Creek and Colfax.

The protection used on the lines was seven-post balanced *CR* relay protection with both phase and ground relays. The circulating induced current in the lines added together in the neutral and caused incorrect operation of the ground relays, opening one breaker on the opposite end of each of the four lines in which induced current was circulating.

The protection used on the lines and the relay which was used to prevent incorrect operation is shown in figure 3. The fact that the induced current flowed in each of the three-phase leads to the balanced relays and this was the only condition which would produce three in-phase currents in the phase leads on a ground fault was used to determine the lockout condition. The current coils of three double directional elements were connected in series with the balanced phase *CR* relays and a zero-sequence potential from star-delta potential transformers was connected to the potential coils of each element.

On a ground fault, potential was produced due to the ground and if induced current existed all three directional elements operated in the same direction. The contacts on each side were connected in series and operated an auxiliary relay to prevent tripping by the ground relays.

On this system a 63-ohm neutral resistor is used so that the zero-sequence potential is always of about the same value and comparatively large. The ground current is limited in value and the ground relays have sensitive settings. The induced current was of sufficient magnitude to operate the ground relays but did not operate the phase relays and it was not necessary to provide a lockout for them.

This scheme was in successful operation for several years but has been removed due to line rearrangements on the towers which removed the induced current problem.

An additional installation was made about 1932 on the 22-kv system using the original shop model of the relay. Balanced protection was used on only one end of the pair of

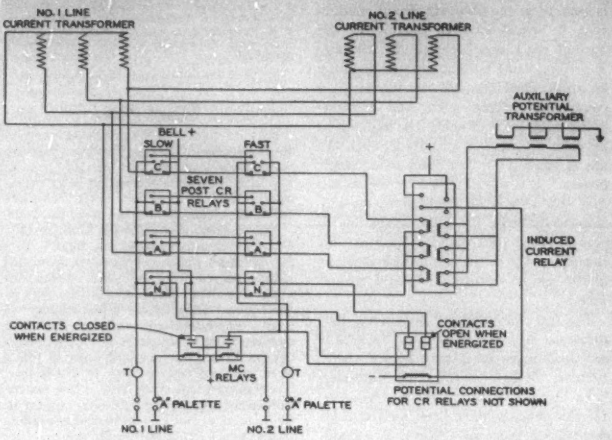

Figure 3. Induced-current relay used with seven-post CR balanced line protection

22-kv lines and one relay could be used in this location to prevent induced-current operations.

W. A. Lewis (Cornell University, Ithaca, N. Y.): Mr. Bancker has performed a service to electrical engineering by collecting in a compact form the references to the numerous problems produced by mutual induction between parallel circuits.

Many of the engineers working in this field have accepted these problems as they arose and solved them one by one, without realizing that the uninitiated would find them difficult when suddenly confronted with one of the more unusual problems. Hence, by describing in a simple fashion all the related problems, Mr. Bancker has provided a convenient and useful reference.

In describing the case of two parallel lines, after one breaker opens, Mr. Bancker shows that the greater portion of fault current may come from the end nearest the fault, even though the circuit breaker at that end has already opened, particularly when the mutual impedance is greater than half the self-impedance. The reason for this is, of course, that the mutual impedance reduces the effective impedance around the loop. Our experience has been that on double-circuit lines, where both circuits are on the same tower or pole, zero-sequence mutual impedance is often as great as seven-tenths of the self-impedance, so that the effect described is usually very important.

Mr. Bancker has explained that the use of distance relays for ground fault protection has been retarded by the mutual effects. As I was a party to the first paper which explained, more than seven years ago, how distance relays could be used for ground-fault protection on parallel lines, to give an accurate determination of the fault location, it is perhaps appropriate to discuss additional reasons why more widespread use of

distance relays for ground faults has not been made. The first of these is cost. With distance ground relays, three relays at each terminal location are required in order to protect against a fault on any phase. In some cases a smaller number of relays has been used, but some form of additional relay is necessary to provide switching so that the relay can be connected to the proper phase for the fault which occurs. This compares with a single ground relay in the schemes of ground protection now in common use. The second difficulty is the effect of fault resistance during a two-line-to-ground fault. Because of the phase relationship between the voltage drop in the fault resistance and the voltage drop in the line, it is found that even with a reactance relay a fault frequently may appear to be closer to the relay location than it actually is, thus sometimes producing an incorrect operation. To overcome this difficulty, it is necessary to arrange the relay so that it will not operate when the fault involves two phase conductors. This necessitates either considerable complication in the relay design or the use of some additional fault-selection device. However, I venture to predict that if single-pole switching of single-conductor faults comes into common use, distance relays will find an extensive application for ground protection.

Bert V. Hoard (Westinghouse Electric and Manufacturing Company, Newark, N. J.): Mr. Bancker has discussed a number of cases where mutual impedance between two or more lines or loops might cause false operation of directionally controlled ground relays. He also discussed certain methods of correction so that the relays would operate properly. Among these was the use of the summation current through all the transformer neutrals for polarizing the directional element, and the fact that if ground wires have been installed or the distance between the respective circuits is large, the effects of mutual induction are materially decreased.

There is available another relatively new method which, we believe, will become increasingly important as it becomes better known. This is the use of a negative-sequence directional element instead of the conventional zero-sequence directional element in a relay, which uses negative-sequence voltage and current for determining the direction of the fault from the relay. In a grounded system for any fault-to-ground there are always negative-sequence currents produced as well as zero-sequence currents. However, the negative-sequence currents must flow in the line conductors; hence their effect by mutual induction practically cancels in any adjacent circuit even though the spacing between circuits is small. It is only on those systems where the wires of the adjacent circuits are not transposed frequently enough and a fault occurs within a relatively long untransposed section that there might be appreciable unbalanced induction in one circuit due to negative-sequence currents flowing in the other.

This method of directional control is available in a new type *CRS* relay which consists of a conventional zero-sequence overcurrent element directionally controlled by a very sensitive negative-sequence directional element and its filters. It will be noted that only two potential transformers connected open delta are required for polarization, while for a conventional zero-sequence voltage-polarized relay three star-connected potential transformers are required; hence, considerable economic saving may be made for many installations when using the new relay.

For loop circuits an instantaneous negative-sequence fault detector may be required and can be obtained with the relay to produce selectivity between a fault in the loop and a fault external to the loop. As an example, in figure 3 of the paper assume the faulty circuit is 60 cycles and is connected to the 60-cycle bus, also that a generator is available and running at the remote bus. During a fault external to the loop this generator feeds power back through the loop, but the negative-sequence current flowing will be small when compared to that flowing when a fault occurs within the loop. The negative-sequence fault detector is adjustable so that it can be set to select between internal and external faults. Its contacts are in series with the directional element so that the zero-sequence overcurrent element cannot trip until the negative-sequence current exceeds the fault detector setting and is in the tripping direction for the directional element. If the above-mentioned generator is not operating, there should be negligible negative-sequence current flowing in the loop circuit for an external fault.

It will be seen that the big advantage of using negative-sequence currents for the directional element and fault detector is that there is a relatively large difference in the negative-sequence current flowing in the loop for an internal fault compared to a fault external to the loop; while if zero-sequence currents were to be used, the mutual induction between circuits would cause the relative currents to be more nearly equal in one branch of the loop for both internal and external faults and thus limit the possibilities of selectivity.

Edward W. Kimbark (Northwestern University, Evanston, Ill.): There seems to be a common impression that zero-sequence current is always associated with ground current. Mr. Bancker helps to correct this impression by giving two instances of circuits in which zero-sequence current is present without any ground current: (1) the loop circuit of figure 3, either ungrounded or grounded at one point, in which a zero-sequence current is induced from another system; (2) a similar loop circuit with a series open circuit of one or two conductors, due for example to the sequential closing of the poles of a circuit breaker. Nevertheless, Mr. Bancker lapses into the common error when he mentions "a true zero-sequence current" in case 2 if the circuit is grounded at two points. A third instance, one not mentioned in the paper, is a short circuit between a conductor of one circuit and a conductor of another circuit, as on a double-circuit line. (By "ground current" in the foregoing is really meant current in the neutral of a grounding transformer, for current will circulate in the earth beneath the loop of figure 3.)

I wish to discuss the circuit of figure 3 in which false operation of zero-sequence ground relays on the loop may be caused by induced currents from a ground fault on another system of the same or a different frequency. If the loop system is grounded through a high neutral impedance, it is especially susceptible to false operation of ground relays because the relays would be given low current settings. There are several respects in which conditions on the loop circuit during induction caused by a ground fault on another system differ from conditions during a ground fault on the loop itself, and some of these conditions might be used to discriminate between the two events. For example, during a line-to-ground fault on the loop itself, there is negative-sequence current and accompanying negative-sequence voltage. The negative-sequence current in the fault is equal to the zero-sequence current, though the distribution of negative-sequence current throughout the system may be somewhat different from that of the zero-sequence current. Negative-sequence relays are not susceptible to induced currents because the negative-sequence mutual impedance between the two systems is negligibly low. Negative-sequence quantities could be used to operate watt-type relays or to operate either the current element or the directional element or both of directional overcurrent relays. Relays working entirely on negative-sequence quantities would respond to all types of faults except three-phase, but this would do no harm. If set too low, they would respond also to unbalanced loads, and this fact, as well as the low value of negative-sequence voltage during line-to-ground faults, would prevent their use on a system grounded through high impedance.

On such a system another means of discrimination can be used. The zero-sequence voltage is high (practically equal to the normal positive-sequence voltage) during a line-to-ground fault, but is low during induced currents. Therefore a zero-sequence voltage relay could be used at each station of the loop to prevent operation of the zero-sequence ground relays unless the zero-sequence voltage should exceed a set value; or possibly the directional elements of the ground relays themselves could be adjusted so that they would not close their contacts except on fairly high torques.

J. A. Elzi (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper calls attention to an important factor in the determination of the magnitude and distribution of zero-sequence currents where parallel lines are involved. The effects of mutual impedance are frequently quite surprising and make it very difficult to make a preliminary relaying layout until a complete study has been made. It is also very important that various system operating conditions and fault locations be investigated because a change in magnitude or direction of current in one line may greatly affect the currents in other lines.

Tests which were made recently on an extensive 22-kv grounded neutral system in which there are numerous parallel circuits in close proximity, demonstrated the above conditions very well. In this particular case, for example, a change of approximately two to one in current distribution between two lines occurred, due primarily to the differences in the effect of mutual impedance for two test conditions. The test values

were in quite close agreement with calculated values, which indicates that the methods of calculation now commonly used and referred to in this paper give very satisfactory results.

E. H. Bancker: As it was hoped, the discussions brought out several interesting cases of induced current experiences to supplement those cited in the paper. Professor Kimbark's and Mr. Hoard's discussion also points out another solution that may be adopted that was overlooked in preparing the paper. Negative-sequence induced currents should be relatively small in comparison with negative-sequence fault currents and, therefore, devices responsive to the negative-sequence should be free from tendency to misoperate for short circuits on other systems. As Mr. Hoard points out, their use sometimes results in a saving because only two potential transformers are required and these may be on the low-voltage side of a power transformer if it is certain that they will be energized at all times.

The main disadvantage in utilizing negative-sequence quantities lies in the fact that methods for deriving them are relatively inefficient in comparison with the methods of deriving zero-sequence quantities. In securing zero-sequence the sum of three current transformer secondaries or of three potential transformer secondaries is added together, giving three times the original quantity. To derive negative sequence it is necessary to use either a network or take the difference of two quantities containing positive-plus negative-sequence terms and positive-minus negative-sequence terms. In both cases the problem of deriving the true negative-sequence component is much more difficult than trying to separate out the zero-sequence component. In some of the instances investigated it was found that the negative-sequence components were too small a proportion of the total current or voltages to permit them to be utilized successfully.

A negative-sequence directional relay constructed from induction-cylinder elements known as the type *CBP* is available for use where the negative-sequence quantities are at least 15 per cent of the positive-sequence quantities. This relay consists of two elements operating upon a common shaft. One element is so connected as to produce a torque equal to the sum of the positive and negative sequence powers, while the other element produces a torque equal to the difference of these two powers. The resultant torque on the shaft is, therefore, either positive sequence or negative sequence, depending upon the connections used. These connections may be switched by a zero-sequence current relay so that the directional relay is normally responsive to positive-sequence power and operates in accordance with this quantity for three-phase and line-to-line faults. The presence of ground current switches the connections of one of the elements so that it becomes a negative-sequence power directional relay for all ground faults.

Professor Kimbark suggests that zero-sequence voltage might be used to distinguish between induced and actual fault current. There are probably cases when it would serve as, for example, in the system shown in figure 3. However, it is not universal in its application because the inducing current may be from the same system, in which case there would be as much zero-sequence voltage in the circulating loop as if the fault had been there. Also, if the system is like figure 2 the current circulating in the transformers produces as much zero-sequence voltage as the same amount of fault current, which conceivably might exist under some different generating condition. Accordingly, zero-sequence voltage is another possibility to add to the list, but is not an invariable selector.

It is hoped that this paper and its discussions will be of value to those who encounter the problem for the first time and wish to find out something about other cases of induced current and the solution adopted for preventing incorrect relay operation.

High-Speed-Relaying Experience and Practice

ABOUT 1930 the manufacturers introduced the high-speed circuit breaker with operating times in the order of eight cycles and at the same time engineers awoke to the possibilities of high-speed or one-cycle relays. The general requirements for such relays were set forth at the time in two papers[1,2] presented before the Institute.

After nearly ten years, a review of the experience gained with such relays seems to be in order, and to that end the relay subcommittee of the AIEE protective devices committee recently circulated a questionnaire among its membership designed to determine this.

This report is based upon the 13 replies received from typical operating companies and also the experience of the manufacturing companies in furnishing high-speed relays during the period. Because of the wide scope of the subject only the salient features can be touched upon here. For more detailed discussion, those interested are referred to the bibliography.

Instantaneous Overcurrent Protection

Most of the reporting companies use instantaneous overcurrent relaying, especially for ground protection, and report excellent performance. The reliability of the system as well as the improvement obtained from minimizing voltage dips and preventing burning down of conductors makes this method distinctly advantageous.

Settings reported for phase relays range from 100 to 200 per cent of the maximum symmetrical through fault current. While considerable benefit in clearing times can be gained in the case of long lines even though using a setting of 175 to 200 per cent, nevertheless one company reports over 1,000 installations using the 100-per-cent setting. An accurate record of the performance of instantaneous overcurrent relays has been kept by this company for two years which shows on steel-tower lines that 85 per cent of all faults are cleared by the instantaneous relays. On the portion of the system using mostly wood-pole line this record showed that 70 per cent of all faults were cleared by the instantaneous relays.

This same company sets the instantaneous ground relays at 110 per cent of the maximum through current and obtains correct operation.

One interesting experience noted was in the case of cable protection utilizing instantaneous relays. Here it seems that the fault is cleared so quickly that the cable will stand all tests and still break down later in service.

Distance-Relay Protection

Distance relays of the high-speed zone type have been used quite extensively for transmission-line protection against phase-to-phase faults. There are two kinds available: the reactance type whereby the distance is indicated from a measurement of the circuit reactance from the relay to the fault, and the impedance type which is based upon the measurement of the impedance.

The information obtained from seven companies who have distance-relay installations indicates that they have, in general, experienced entirely successful and satisfactory operation. Some unnecessary tripping has been occasioned

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Paper prepared by J. H. Neher, chairman; C. A. Muller, L. F. Kennedy, G. W. Gerell, and R. M. Smith; all members of the AIEE relay subcommittee.

1. For all numbered references, see list at end of paper.

by out-of-step conditions which are, of course, liable to cause operation of any type of relay. Also, on some of the earlier type distance relays constructional defects have appeared and been eliminated.

Analyses of the effect of synchronizing surges and out-of-step conditions on the distance relay have been made so that trip-outs which were formerly classed as incorrect relay operations can now be shown to be the result of the complex conditions attendant upon out-of-synchronism situations.[3,4]

In addition to unnecessary tripping under out-of-step conditions, there have been trip-outs on wide angular swings in cases where the system would have pulled back into step if permitted to do so.

It should be borne in mind that the contacts of the directional and impedance units should be carefully adjusted to insure proper time co-ordination particularly to take care of restoration of normal conditions on a heavily loaded line. A few unnecessary trippings have occurred because of incorrect co-ordination adjustments.

The distance relay is not generally applicable to protection against single-phase-to-ground faults unless elaborate methods of compensation are employed,[5] and as a result, very few installations of this type of protection have been made. One company, however, reported a number of installations of uncompensated impedance relays used for ground protection of important lines. On the whole, these have been successful when carefully applied on steel-tower lines with ground wires, but not otherwise.

No doubt in this case the successful operation was occasioned principally by the presence of the ground wire and lack of multiple neutral grounds. The ground wire has the effect of bringing the zero-sequence and positive-sequence impedance values closer together, thus mitigating the necessity for compensation.

Pilot-Wire Protection

The use of pilot-wire protection for relatively short lines has been constantly increasing and general use has been made of both a-c and d-c systems. The a-c systems are of the differential variety comparing currents at the line terminals usually with a relay having a percentage characteristic. The d-c systems, like the carrier-current protective systems, are of the directional comparison types, but use has been made of both the blocking type paralleling the carrier-current protective equipment, and the tripping type.[6,7] The tripping type appears to be most popular largely because it uses simpler relay equipment, although its application is somewhat more limited than is the case with the blocking type. All of these systems use relays operating in 0.01 second or less with a very marked tendency to the greater use of one- or two-cycle relays. Operating experience with these systems has been very good. Most of the d-c systems employ telephone-type pilot wires and the reports indicate that these circuits are giving very reliable service.

A recent development in a-c pilot-wire protection involves the use of extremely sensitive pilot-wire relays fed from phase-sequence networks which permits the use of a single telephone pair as the pilot wire to obtain protection against all types of faults.

Carrier-Current Pilot Protection

Carrier-current relaying has not as yet been adopted by many operating companies. However, such experience as those companies using it have obtained, indicates that distinct operating advantages are possible. The equipment itself being comparatively new might be expected to disclose numerous difficulties. Operating records of one company with many installations indicate that 1.2 per cent of the operations were incorrect, about one-third of which were chargeable to the carrier equipment.[8] The majority of the faults in the carrier equipment were due to a certain physical arrangement of equipment which failed to provide adequate weatherproofing. The majority of the faults in the relays were due to imperfections in relay or circuit design which have since been corrected.

Balanced Protection of Parallel Lines

Modern high-speed balance relays have a very definite application to many power systems,[9] and many installations have been made of both the current-balance and the cross-connected directional relay types. Such protection, of course, is only effective for single-line faults at a time when both of the paired circuits are in operation, and other relays must be installed to provide protection during single-line operation or in the case of double-line faults.

The application of balanced protection must be considered carefully since there are a number of factors tending to cause incorrect operations. Experience has shown that attention should be given to matching reasonably the current transformer characteristics on the two or more lines supplying the relay. If this is not done a through fault may readily cause operation of the balance relay, such phenomena having been reported on at least one system.[10]

Considerable difficulty has been experienced in applying this type of protection to lines which terminate on different bus sections interconnected through a tie breaker which may be tripped automatically and thus destroy the balance of the lines.

Protection of Lines With More Than Two Terminals

Lines having more than two terminals usually present relaying difficulties. There are available no schemes or methods of relaying especially designed for this application. The high-speed schemes available for two-ended lines such as distance, instantaneous overcurrent carrier, and pilot wire are used on tapped lines, but the high-speed protection rarely extends to all posts of the tapped line. The high-speed coverage with distance and overcurrent to be expected depends on the relative line lengths from the tap point of the terminals and will vary, if the equivalent impedance beyond each terminal changes.

Carrier and pilot systems using a directional indication for the basis of discrimination may also present difficulties because power may initially flow out of the section at one terminal for an internal fault, thus blocking the tripping of all terminals. This trouble can usually be cured by the use of high-speed distance or overcurrent backup relays.

Nine companies reported that they had no tapped or branched lines on high-voltage systems, hence had no application of high-speed relaying for tapped or branched lines. The schemes submitted by the other four companies were all based on the fact that the magnitude of the short-circuit current for faults in the section where it was not desirable to relay the line was not sufficient to operate the high-speed relays. In cases where it was impossible to accomplish this by the above means, either pilot-wire or carrier-current relaying had to be used.

Bus Protection

High-speed relays of either the overcurrent or impedance types have been applied in various bus protective systems and experience seems to indicate that satisfactory operation is being obtained. This is discussed in a report on bus protection currently presented before the

Institute (AIEE TRANSACTIONS, volume 58, 1939, pages 206–11).

The application of the complete differential system with instantaneous overcurrent relays is becoming more common, although it is recognized that there are conditions which may result in a sizeable difference current flowing in the differential circuit during the first few cycles of a fault. From the available data it appears relatively safe to use instantaneous overcurrent relays on the bus differential system if the current transformers are chosen high enough in ratio so that they are never subjected to more than ten times their rated current under any condition.

A new development during the past year is the harmonic-restraint type of relay which offers a method of obtaining fast clearing of internal faults and at the same time preventing incorrect operation on the initial transient in the case of through faults.[11]

Effect of Transients on High-Speed Relays

The fact that transients are encountered which may affect relay operation has been reported from several sources. The effect of these transients on high-speed relays may either cause incorrect or unnecessary operations or operate to prevent operation of the relay when desired until the transient has disappeared.

Many of these transients have been present without causing any incorrect operation with the older types of time-delay relays. They become of more importance with the high-speed devices capable of operating in a total time of one or two cycles.

The most commonly encountered forms of transients and the corrective measures available at the present time are given in table I. A few general comments in relation to this table may be in order. The effect of asymmetrical current waves on overcurrent or distance relays is, of course, obvious. Operating experience, however, indicates that so few short circuits produce sufficient offset to cause incorrect operation that the fact may in general be disregarded except in the case of equipment installed on generating station busses.

Transformer magnetizing current is a well-known phenomenon which all transformer differential relays for years have attempted to take care of either by time delay or desensitizing equipment. The new factors introduced within the past year are the use of a tripping suppressor attachment or a harmonic restrained relay which recognizes the difference in wave form which occurs during the period of magnetization.

Table I. Types of Transients Affecting the Performance of High-Speed Relays

Type of Transient	Type of Protection	Result	Corrective Measures
Asymmetrical current wave	Instantaneous overcurrent or distance relays	Over reaching. Incorrect tripping	Use of transient shunt
Transformer magnetizing inrush	Transformer differential relays	Incorrect tripping	Use of a desensitizing arrangement, tripping suppressor, or harmonic restraint
Expulsion-gap operation	Instantaneous overcurrent or distance relays	Incorrect or unnecessary tripping	Add time delay relay in tripping circuit
Nonsimultaneous breaker-pole closure	Ground relays	Incorrect tripping	None
Current-transformer saturation	Differential protection, particularly for busses	Incorrect tripping on external faults	Change in current transformers or use of current or harmonic restraint
Potential-device secondary degree transient	Distance relays	Slow tripping	None

The use of expulsion gaps obviously subjects relays to short-circuit conditions for a short period of time, and if the relaying is to be fast under other conditions unnecessary tripping will result. It seems more desirable to use the existing high-speed devices for this service and enable them to ride over expulsion-gap operation by adding a definite-time auxiliary relay in the trip circuit.

In general nonsimultaneous breaker-pole closure has not been a source of trouble, although two or three cases have been reported where a transient maintained itself in the residual circuit long enough to cause unnecessary relay operations. The methods of correction have varied with each particular case, being largely dictated by the types of relays already installed. No general solution is available.

Potential devices in many cases will have a transient between the occurrence of a fault and the time the secondary voltage reaches its new level. This will prevent operation of distance relays until the voltage becomes low enough for the relay to operate. There is no solution to this available at the present time.

Conclusions

While it is apparent that the "ideal relay scheme" so earnestly sought after[12] has not yet been found, nevertheless it may be said that the efforts made in that direction have not been in vain, and that the following conclusions are evident.

1. The instantaneous overcurrent relay provides a simple inexpensive means of obtaining high-speed relay protection over a considerable portion of the line length and offers possibilities in the way of general relay-system improvement of which, to date advantage has not been fully taken.

2. Distance relays have proved themselves reliable if carefully applied and maintained, and are widely used. However, the relative complexity of this device, its general restriction to phase-to-phase fault protection only, and the fact that instantaneous protection is not provided for the entire line length, have caused engineers to look elsewhere for the ideal relay protection.

3. Carrier-current or metallic pilot protection appears to be the first choice of high-speed protective systems whenever the expense is justified. Experience has indicated that a remarkable degree of reliability can be expected from the communication channel whether it be of the carrier-current or metallic type.

4. High-speed bus protection can be successfully applied if proper steps are taken to prevent the operation of the differential relays on transients.

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Discussion

S. L. Goldsborough (Westinghouse Electric and Manufacturing Company, Newark, N. J.): As is pointed out by the authors, some unnecessary and, at the time, unexplainable trip-outs of high-speed distance relays have been caused by out-of-step conditions. This should be no reflection on the distance-type relay, since it is obvious that it, as well as any other type of relay, should view the out-of-step conditions as representing an actual fault. Nothing effective was done to prevent the operation of distance relays on these conditions, other than the analysis of the situation, until the advent of the high-speed carrier systems. The availability of a carrier signal seemed to render the problem of supplying out-of-step blocking easy of solution. However, at least in the case of the carrier system employing a three-zone impedance relay, it turned out that the carrier signal played a very minor role in the operation of the out-of-step blocking scheme developed. In other words, the identical out-of-step blocking system used with the stepped-type impedance-relay carrier system can be used to provide out-of-step blocking for conventional impedance relays without carrier. The only function of the carrier signal in the out-of-step blocking scheme is to enable the relays to trip on an internal three-phase fault after the system is out of synchronism. Therefore, when this out-of-step blocking system is used on impedance relays without carrier, the ability to trip for three-phase faults during out-of-step conditions is secured only when the backup time element is arranged not to be blocked by the out-of-step relays.

Concerning the tendency of distance relays to trip on wide angular swings which would not result in out-of-step conditions, analysis has brought out that the probability of tripping on wide angular swings is minimized by using the same currents to actuate both the impedance element and the directional elements. For instance, if delta current is supplied to the impedance element then delta current should be supplied to the directional element and if star current is used it should be supplied to both elements. This precaution will not prevent all trippings on wide angular swings but the tendency to trip will be materially reduced.

While the 13 typical operating companies contacted are doubtless a fairly representative cross section of the field, it is felt that the paper would have been more valuable, both in the amount of information obtained and the number of conclusions deducible therefrom, if a large number of operating companies had been contacted.

V. E. Verrall (General Electric Company, Philadelphia, Pa.): This summary of high-speed-relaying practice comes opportunely after a period of intense development at a time when applications of high-speed relays will be made with increasing frequency. During this development we have met a succession of difficulties with transient electrical conditions, some in the relay windings and some in the protective circuit, conditions which were not important with the induction-disk relays because the transients were all over by the end of two to three cycles. In Europe the difficulties were avoided by introducing time delay of the order of six cycles before the relay is allowed to complete the tripping circuit. In this country we have devised means for overcoming each transient trouble. For example, modern distance-relay dephasing circuits are made electrically deadbeat; directional-relay potential circuits are provided with time constants which will give correct action. As time went on these snags have become fewer and fewer and now the one-cycle relay seems to be thoroughly practical.

Nevertheless, it may be wise to avoid the maximum relay speed when such speed will not add materially to the performance of the protective system. In general one-cycle relays can be adjusted to give a time delay of two or three cycles, thus achieving a desirable margin of safety. In a distance relay, for example, an extra cycle or two in the response of the directional element avoids the need for the refined co-ordination of directional and impedance contacts mentioned. The ill effect of nonsimultaneous breaker-pole closure upon ground relays will usually be avoided by using induction relays of the high-speed type with a few cycles time delay under these conditions instead of relays working in less than one cycle.

While the operation of carrier equipment has been successfully controlled during out-of-step conditions, nothing appears to have been done in this country to control distance relays. It is a simple matter, however, to prevent undesirable tripping of distance relays by a low-set fault detector which opens the trip circuit if the line impedance changes slowly indicating a power swing as opposed to the instantaneous change in impedance when the line is short-circuited.

About 80 General Electric reactance relays are now being used for ground faults. Satisfactory operation has been reported over the last three years. Reactance relays are much preferable to impedance relays on ground faults because there can be very appreciable resistance in the fault contact and ground circuit which is liable to vary between wet and dry periods.

In table I of the paper the use of the transient shunt is suggested for preventing undesirable operation on asymmetrical current waves. A simpler solution is the use of induction-type relays, such as the high-speed induction cup, which are substantially unresponsive to the d-c component of the current wave.

Paul O. Langguth (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): While the committee states that no solution to the problem of potential-device transients is available, our experience indicates that satisfactory relay operation may be obtained despite these transients. We have used these applications under field short-circuit conditions. The tests on the Indianapolis system[1,2] show that the high-speed relays energized from potential devices gave the high-speed clearance of faults for which they were installed. There were no false or delayed operations. These results would seem to indicate that with proper co-ordination of potential device, auxiliary transformer, and relay characteristics, satisfactory operation of high-speed relays from potential devices is entirely reasonable and to be expected.

Although transient disturbances may be expected in a loaded potential device (due to the combined network of capacitance and inductance) still the combined circuit of burden and potential device constitutes essentially a series circuit of R, L, and C. In such a circuit it is well known that as R is increased relative to L and C the transient becomes of shorter duration and the phenomena changes from oscillatory to deadbeat as R passes the critical value $R^2 = 4L/C$. The R in this case represents essentially the burden resistance. Thus it can be seen that at light burdens the resistance becomes high and the transient is nonoscillatory. Even with full rated burden on the devices the magnitude of the damped wave may be reduced to the point where it will have negligible effect on the operation of high-speed relays.

In view of the satisfactory performance obtained on the Indianapolis and other systems there must be some differences in the application which are not immediately obvious. Therefore, it would seem desirable to analyze further those systems giving slow operation in order to discover the specific causes of unsatisfactory operations.

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J. R. North (The Commonwealth and Southern Corporation, Jackson, Mich.): This report of the relay subcommittee is very interesting and decidedly encouraging as regards the use of high-speed relaying. However, referring to the second paragraph under "Distance Relay Protection," it might be inferred that distance relays have, in general, given entirely successful and satisfactory operation except for some unnecessary tripping occasioned by out-of-step conditions. Conclusion number 2 mentions the relative complexities of distance relays and the necessity for their careful application and maintenance.

The experience of one of our companies with an installation of some 30 high-speed zone-type reactance relays may be of interest.

These relays were installed in 1931 and, from the beginning, numerous incorrect and unexplainable (at the time) operations occurred. These operations were studied and discussed with the manufacturers. Several steps were taken to improve the performance of the relays and also the performance of the 161-kv bushing potential devices which supplied the relays with potential.

The potential burden of the relay starting unit was much higher at low voltage than at rated voltage and this accentuated the

ratio and phase-angle errors of the bushing potential devices. The performance of the starting unit was improved by bringing three-phase potential to the relay and removing the tuned resistance-capacitor unit, which caused the high burden at low voltage. This change decreased the relay pickup from 12 to 6 amperes and it was therefore necessary to add a resistance to compensate for this.

The bushing potential devices were given elaborate phase-angle and ratio tests in the field, and it was found that their variations in ratio and phase angle not only gave incorrect ohmic indication, but that this ohmic indication varied for maximum and minimum fault conditions. The ratio error tended to reduce the relay pickup current, thus, making the relay more apt to operate under low-current conditions.

The bushing-potential-device networks were subsequently rebuilt to give more efficient operation but, even after these changes and with the relays having constant burden, there were still a number of incorrect operations. During the following year there were 8 correct and 3 incorrect operations on phase faults and 15 incorrect operations on ground faults. In this classification, which is based on careful analyses of oscillograms, faults which involved two or more phases, with or without ground, are termed "phase faults." The term "ground faults" applies only to single line-to-ground faults.

These relays were provided for phase fault protection only and were not intended to operate on ground faults; however, the oscillograms indicated that the secondary phase currents during ground-fault conditions on this extensive isolated-neutral system might be as high as 20 amperes. The phase angle varied widely but appeared to be generally in the range of 45 to 75 degrees, leading the power-factor position.

After further detailed study and discussions with the manufacturers, it was the consensus of opinion that possible causes of the trouble included:

(*a*). Improper angle of maximum torque of starting unit.

(*b*). Excessive wipe of ohm-unit *A* contact.

(*c*). Combination of load and fault currents giving incorrect distance measurements.

(*d*). Errors in potential devices and current transformers.

(*e*). Proximity effect of adjacent relays.

It was decided to make further changes in the relays to eliminate the difficulties. The auxiliary resistance in series with the potential-coil circuit, which had been installed to bring the pickup back to its original value, was replaced with a reactance unit in order to shift the angle of maximum torque from unity power factor to 45 degrees lag. This change in the angle of maximum torque tended to prevent incorrect operation on ground faults and to improve operation on two-phase and three-phase faults.

Auxiliary wye-delta-connected current transformers were installed further to reduce the operations on residual ground current.

The adjustment of the relay mechanism was carefully checked and the contacts readjusted where necessary.

The changes outlined herein have resulted in very much improved operation of these relays according to the records to date, and it is felt that the detailed analyses of the conditions in the field, including the tests on the bushing potential devices and relays, were decidedly worth while. No doubt this work has also assisted materially, although indirectly, in the development of the improved present-day designs of distance relays.

In view of this experience, it is our opinion that proposed applications of high-speed zone-type relays should be carefully investigated, weighing the over-all gains against the complexities and possible operating difficulties. The performance of the high-speed unit and the characteristics of the potential and current supply require careful co-ordination.

E. L. Harder (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): This report, having its basis in the actual operating experiences of numerous companies, forms a most valuable guide to protection engineers.

The effect of potential-device transient on distance-relay speed would bear further analysis. For faults over a considerable portion of the operating range of an impedance element the voltage does not need to fall nearly to its new level before a large operating force is available. In view of the extremely short time constant of decay of the error voltage the time extension is scarcely measurable in this region. Near the relay balance point the relay time increases even when tested with an abrupt voltage change. Due to the increased relay time in this region, the short-duration transient becomes of small importance. It would seem rather difficult to separate time extension due to proximity to the balance point from that due to potential-device transient. It would be interesting to know whether this phenomena has been observed and measured or whether it has been anticipated on theoretical grounds.

Under the heading of bus protection the guide given for freedom from current-transformer transients, namely current not to exceed ten times transformer rating, would need to be used cautiously.

It is apparent that the assumption of average design and ten times current leaves the rather important variable factors of d-c time constant and relay burden unaccounted for. The time constant may vary over the range 0.3 to 0.003 or possibly more in different instances, longer time constants of 0.1 to 0.15 seconds being typical of large generator busses. Burden, while varying less from an average value, is likewise a very important factor, particularly the resistance component.

Methods are now available for calculating without too great complication what differential current will occur. Where long time constants or high burdens are encountered the rough guide should be used with caution and it is considered preferable to calculate the differential current.

L. F. Kennedy (General Electric Company, Schenectady, N. Y.): Mr. North has presented the case history of a distance-relay application which did not operate successfully until certain changes were made as the result of field tests. The undesirable operations were due mainly to three causes, namely: (*a*) conditions existing on an extensive high-voltage, isolated-neutral system when one conductor was grounded, (*b*) variation in ratio of potential devices, and (*c*) improper relay-contact adjustment. The operations resulting from the conditions existing with one phase grounded were correct as far as the relays themselves were concerned, but actually they were the consequence of what was later recognized as an incorrect application of the relays as originally designed. In other words, the relay had not been correctly designed for this particular application. Often complete data are lacking in cases of early application of new devices so that changes such as outlined by Mr. North become necessary as greater experience is gained. This experience indicates the necessity for full knowledge by all concerned of system, relay, and associated equipment characteristics if correct operations are to be obtained.

In regard to the general use of potential devices, these are giving satisfactory operation when properly applied. To obtain the best results proper consideration must be given to the ratio, particularly under limiting fault conditions. There are existing data showing a transient in the voltage circuit that tends to delay operation slightly but as indicated by Mr. Harder, this is not generally noticeable with present over-all clearing times.

Mr. Langguth has mentioned that this transient may be controlled to some extent. It is not generally necessary to have such a refinement today, but it would be highly desirable to have this information more generally available.

Some of the discussers have indicated that it may be desirable to slow down the speed of relay response in order to eliminate some of the possibilities of incorrect operation. Through the co-operative efforts of manufacturers and users, we are now at the point where we have overcome most tendencies of high-speed relays to operate incorrectly. It is our feeling that the work done to date has reached the point where practically the same degree of reliable operation can be obtained with high-speed relays as with lower-speed devices.

With the availability of breakers operating in less than eight cycles any concerted move to slow down relay operation seems to be a backward move and it is our recommendation that the present policy of making high-speed relays thoroughly reliable even with one-cycle operating times be continued.

An Amplifier-Wattmeter Combination for the Accurate Measurement of Watts and Vars

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Synopsis: As part of a program of improvements made to the network analyzer in the electrical-engineering research laboratory at the Massachusetts Institute of Technology, an instrument to measure watts and vars has been devised which imposes a negligible burden upon the network, is rapid in response, and has an error less than one-half per cent of full scale. The instrument consists of (1) a semistock electrodynamic wattmeter, (2) a negative-feedback vacuum-tube amplifier, and (3) a phase-shifting network. When the equipment is once assembled the presence of the amplifier may be ignored and the instrument used thereafter as any portable instrument. The principle of instruments of this kind has other important applications in the field of electrical measurements.

Purpose of the Instrument

THE development of the instrument described herein forms part of a program of improvements intended to overcome the limitations of certain measuring instruments which were originally provided for use with the MIT network analyzer[1] when it was built jointly by the department of electrical engineering at MIT and the General Electric Company during 1928–29. Certain instruments which possessed the characteristics necessary for this application, and which could be constructed at that time with reasonable cost, had various undesirable limitations, the chief one being slow response.

The nature of the characteristics required of certain instruments used with a network analyzer can best be explained by describing briefly its function. Such a device permits electrical representation in miniature of an actual power system. The MIT network analyzer operates at 60 cycles, and is equipped with sufficient elements to represent the electrical essentials of a power system comprised of as many as 16 generating stations with interconnecting lines and loads. In most studies, whether they be load-distribution, steady-state, or transient-stability measurements of volts, amperes, watts, and vars at numerous points within the network are to be performed. Since an average load study may often necessitate a thousand or more readings during a day's work, the need for measuring instruments that are rapid in response without a sacrifice in accuracy is apparent. The accuracy requirement imposes unusual limitations upon the measuring instruments, and unfortunately it is not always satisfied merely by the use of accurate measuring instruments. In addition, the burden represented by the instruments must have negligible effect upon the quantities they are to measure.

When it is necessary to perform measurements at the terminals of the equivalent synchronous machines, the commercially available portable instruments of short response time can be used, since it is not difficult to correct for whatever effects their losses introduce. For convenience, these instruments usually remain connected at the machine terminals throughout a study and are ignored while measurements are made at points within the network.

Unfortunately, when commercially available portable instruments are connected at points within the network, their burden often appreciably disturbs the electrical conditions previously established. The labor then necessary to readjust the circuits to compensate for these disturbances, or the tedious calculations involved if the data are corrected analytically for them, in part defeats the purpose of a network analyzer. To render these disturbances negligible the impedance of the current coil of an instrument connected in the network and the admittance of the potential circuit of an instrument connected at the point of measurement in the network, must be much smaller than are normally encountered in commercially-available portable instruments having the desired sensitivity, accuracy, and speed of response.

When the MIT analyzer was built the quantities generally measured were volts, amperes, and watts. The low-burden voltmeters and ammeters then provided were thermocouple instruments and the low-burden wattmeters had suspended moving elements. All these instruments were slow in response on account of their necessarily low burden. After the analyzer had been used for several years, developments in the art of power-system analysis placed more emphasis upon the knowledge of vars than had been the case originally. To measure vars, a phase-shifting transformer was used to make available at the terminals of a wattmeter a voltage in quadrature with the voltage at the point of measurement. To speed the measuring process, a commercially available low-power-factor portable wattmeter having low current-circuit impedance was used as the indicating instrument for watts and vars, and its potential-circuit burden supplied from the phase-shifting transformer. This procedure relieved the network of wattmeter potential-circuit burden and permitted the use of a rapid-response instrument. However, it still necessitated: first, to measure watts, the manual adjustment of the secondary voltage of the phase-shifting transformer to equal in magnitude and angle the voltage at the measuring point; and second, to measure vars, the rotation of this voltage into quadrature with the voltage at the measuring point. Thus the time required to make these measurements was considerable.

The instruments originally used to measure voltage within the network have been replaced by a single a-c rectifier-type voltmeter of 1,000 ohms per volt. The burden of this voltmeter is negligible, it reaches full deflection in a fraction of a second, and is provided with an adjustable shunt across its moving coil to permit rapid standardization by comparison with a standard portable electrodynamic voltmeter. The instrument described hereinafter has been developed to replace the apparatus originally used to measure watts and vars, with the object of reduc-

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The authors acknowledge the assistance given them with this problem by many of their colleagues at the Massachusetts Institute of Technology. They also wish to thank R. N. Slinger of the General Electric Company for his helpful comments made during the preliminary discussions on this problem, P. J. Jacobs, Jr., now of the Allis-Chalmers Manufacturing Company, who carried out the early experimental work, and A. H. Wolferz of the Weston Electrical Instrument Corporation for his co-operation in obtaining a suitable wattmeter.

1. For all numbered references, see list at end of paper.

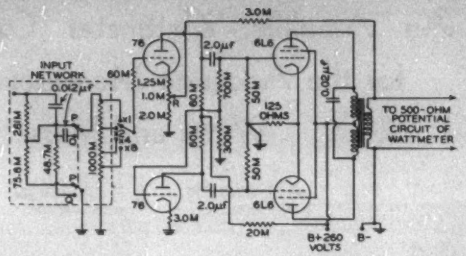
ing the time required to make these measurements. In a manner discussed toward the end of the paper, this instrument is also used for the rapid measurement of current in polar or complex form.

Form of the Instrument

Since it was expected that only one instrument of this type would be needed for the particular application, it appeared desirable to use stock apparatus wherever possible in order to avoid excessive costs. In accordance with this idea it seemed logical to consider continuing the use of an electrodynamic wattmeter for the basic indicating member of the instrument. Then, to reduce the time to take measurements it was proposed to operate the wattmeter in conjunction with a vacuum-tube device that would supply all, or part of, the wattmeter energy for operation, and, at the same time, eliminate the phase-shifting transformer. Hence, a study was made to determine whether vacuum-tube units would be required for both potential and current circuits, and if both were not required, which would be preferable.

If a single vacuum-tube amplifier is used to energize the wattmeter current coil, its input circuit could consist of a low-resistance shunt connected in series with the network. The burden imposed by the wattmeter potential circuit must then be made negligible by decreasing its admittance and hence decreasing the ampere turns provided by the usual moving-coil system if assembled from stock wattmeter parts. Since the rapidity of motion of the moving-coil system in an electrodynamic instrument depends on the product of the ampere turns of the moving coil times the ampere turns of the stationary coil, a moving system of low burden and short response time necessitates more than normal ampere turns for the fixed coil, in this case the current coil. It was found that to provide sufficient ampere turns by suitable stock coils would overload the current coil to a degree that would make its temperature rise excessive. On the other hand, if a single vacuum-tube amplifier is used to energize the wattmeter potential coil instead of the current coil, its design is less difficult. The admittance of its input circuit can be made small enough to impose a negligible burden on the network, and the impedance of the wattmeter current coil can be made small enough to comply with the limitations imposed by the analyzer application, and both restrictions thus satisfied with one amplifier. A 90-degree phase-shift circuit can be inserted in the amplifier input network to make possible the measurement of vars. However, when the impedance of the current coil of a wattmeter of conventional design is reduced, the number of turns in the coil is usually reduced. Thus, the potential coil must supply more than normal ampere turns to give the ampere-turn product required by a rapid and rugged moving-coil system. Fortunately, the potential circuit in most designs of stock wattmeter operates with a larger margin of safety in regard to heating than does the current circuit, and it is possible to establish an ampere-turn product in the potential coil sufficient to provide a satisfactory instrument without serious heating.

Figure 1. Circuit diagram of amplifier



For these reasons, the instrument consists of a single amplifier which provides the potential-coil current of a semistock electrodynamic wattmeter whose current-coil impedance is small enough to have negligible effect upon the electrical conditions of the network.

Design of the Wattmeter

Because there appears less freedom in the design of a wattmeter from stock parts than in the design of an amplifier, the wattmeter was selected first and the necessary amplifier then designed. The specifications established for the wattmeter limit its current-coil impedance and specify its sensitivity. The ampere-turn product then required, and hence the ampere-turns to be provided by the potential coil, necessitates a compromise between the allowable time for the pointer to come to rest and the degree of ruggedness desired in the instrument.

The criterion which limits the magnitude of the current-coil impedance is the magnitude of the smallest impedance element used in the network analyzer. More specifically, if inserting a current coil into a network is not to disturb appreciably the electrical conditions of the network, the current-coil impedance Z_i must be negligible compared with the impedance Z_L measured looking into the network from the point where it is opened up to insert the coil. The criterion established was that the disturbance would be considered negligible provided the value of the impedance Z_i was less than one per cent of the impedance Z_L. The impedance values encountered in a study are a function of the base quantities and with the analyzer connected for the customary 200-volt two-ampere base, unit impedance* is 100 ohms. Operating experience has indicated that impedance elements less than 0.10 per unit on the system base are seldom encountered, although in an extreme case two circuits each represented by about a 0.10 per-unit impedance might be connected in parallel. For this condition it can be shown that the minimum value of the impedance Z_L ranges around 10 ohms; therefore the impedance of a current coil must be less than 0.10 ohm.

The current coil of a 5- or 7½-ampere wattmeter for low power factors has an impedance close to this value and was therefore selected. When used with the analyzer the working coil current is determined by the magnitude of the quantities to be measured rather than by temperature considerations. Since unit power is 400 watts or a convenient multiple thereof, and, since it is desired to indicate with reasonable accuracy about a 0.01 per-unit load or 4 watts, an instrument having a sensitivity of about 75 watts full scale, 100 volts, unity power factor was considered reasonable.

A moving-coil system was next desired that would have a restoring torque

* Power-system computations are usually made in terms of per-unit quantities, where unit or base kilovolt-amperes is an arbitrarily chosen magnitude, unit voltage is normal voltage, unit current is equal to $\frac{\text{base volt-amperes}}{\sqrt{2}\text{ volts line-to line}}$, and unit impedance is equal to $\frac{(\text{volts line-to-line})^2}{\text{volt-amperes}}$. To study a system on the MIT analyzer, a single-phase representation is used and convenient unit quantities are 400 volt-amperes, 200 volts, two amperes, and 100 ohms. Thus, on this analyzer 400 volt-amperes represents unit system kilovolt-amperes, 200 volts represents unit system voltage, and two amperes represents unit system current. Other analyzers use different base quantities.[4]

sufficient to provide a reasonably fast and rugged instrument, and yet not so large as to require an abnormal number of potential-coil ampere turns to provide the necessary ampere-turn product with about 0.75 ampere in the current coil. The moving system of a Weston model 310 portable electrodynamic wattmeter for low power factors was made suitable for this purpose by (1) use of restoring springs that have approximately 70 per cent of normal torque, (2) operation with approximately twice the customary potential-coil current, and (3) slight modification of the air-damping system. The wattmeter as assembled gives full-scale deflection at unity power factor with 0.60 ampere in the current coils, and is calibrated zero to 60 watts. A series-parallel current-coil connection and potential multipliers provided as described hereinafter, permit appreciable increase in range. For convenience in calibration a 100/200-volt potential circuit is provided. Table I summarizes the principal design constants of the wattmeter. Although the above modifications to a stock portable wattmeter may make it somewhat less rugged, they are not considered serious because it is removed from the central metering desk only when taken to a standardizing laboratory.

Design of the Amplifier

If an amplifier is to be suitable for use as a component of a measuring instrument for a network analyzer, it should satisfy the following specifications:

(*a*). A constant ratio of input voltage to output current throughout its working range.

(*b*). A high degree of stability during long periods of time.

(*c*). A high degree of freedom in regard to the interchangeability of tubes of the same type.

(*d*). A negligible phase angle between input voltage and output current.

A type of amplifier whose performance approaches the above specifications is one whose circuit employs the principles of negative feedback,[2,3,4] and is accordingly used in this instance. A circuit diagram is given in figure 1. The form in which the negative feedback is employed in figure 1 results from the operating conditions encountered in this application. To avoid supplying an excessive amount of energy from the amplifier, it is desirable to energize the wattmeter potential circuit at as low a voltage as practicable. However, it is not satisfactory to energize only the potential coil, unless the change in its resistance due to temperature rise has negligible effect on the desired ratio of coil current to amplifier input voltage. Since temperature rise may often be appreciable (see table I) the amplifier could be designed using inverse feedback in a manner that tends to maintain the ratio desired to a high degree in spite of the effects of temperature rise in the potential coil or other elements which form part of the output circuit. To do this a resistor having negligible temperature coefficient would be connected in series with the potential coil, and a percentage of the voltage drop across this resistor fed back into the input circuit of the amplifier, so as to oppose the applied input voltage.

To determine the quantity of feedback voltage required, it is necessary to investigate the dependence of the amplifier performance on the expected variation in output-circuit resistance resulting from temperature rise. The elements which probably contribute most to this effect are the potential coil and the output-transformer windings. Using the customary methods of analysis[2,3], the voltage drop E_2 developed across the feedback resistor in the output circuit, is related to the voltage E_1 applied to the amplifier by the expression

$$E_2 = \frac{\mu E_1 - I_c Z}{1 + \mu\beta} = I_c R_0 \qquad (1)$$

where

- μ is the ratio of the voltage appearing at the primary of an equivalent 1:1 output transformer, to the grid-cathode voltage of the first tube
- β is the fraction of the voltage E_2 fed back into the input circuit
- I_c is the potential-coil current
- Z is the sum of the impedance Z_T of the output transformer and Z_c of the potential coil
- R_0 is the feedback resistor of negligible temperature coefficient connected in the output circuit

By rearranging equation 1 the transconductance g_m, which is equal to I_c/E_1 becomes

$$g_m = \frac{\mu}{R_0(1 + \mu\beta) + Z} \qquad (2)$$

From which

$$\frac{dg_m}{dZ} = \frac{-\mu}{[R_0(1 + \mu\beta) + Z]^2} \qquad (3)$$

From equation 3, the absolute fractional change $\Delta g_m/g_m$ in g_m caused by a change ΔZ in Z, when all other parameters are constant, is,

$$\frac{\Delta g_m}{g_m} = \frac{\Delta Z}{R_0(1 + \mu\beta) + Z} \qquad (4)^*$$

Table I

Potential circuit	
Potential-coil current (ampere)	0.08
Ampere turns	24
Resistance of moving coil (ohms)	45
Temperature rise of moving coil (deg C)	12.7
Inductance of moving coil (henry)	0.0041
Torque per spring at 100 degrees (milligram-centimeters)	70
Number of springs	2
Current circuit	
Working current series connection (ampere)	0.6
Maximum current series connection (amperes)	5
Number of current coils	2
Turns per coil	34
Resistance per coil (ohm)	0.034
Ampere turns (with usual working current)	40.8
Movable system	
Undamped period (seconds)	1.02
Damping factor	18.3
Time to get reading at two-thirds scale (seconds; approximate)	2.5
Torque/weight$^{1.5}$ (milligram-centimeter for 100 deg/grams$^{1.5}$)	33.4

Equation 4 permits calculation of the magnitude of the resistor R_0 necessary to maintain any desired amount of constraint on g_m for the predicted variation ΔZ resulting from temperature rise, when appropriate values are assigned to μ and β.

In any actual circuit the parameters appear as complex quantities, but for this particular amplifier a real value is required for g_m because the potential-coil current must be in phase with the voltage applied to the amplifier. Measurements performed on an amplifier assembled so as to make $\Delta g_m/g_m$ essentially independent of anticipated changes in Z due to temperature rise, showed that the phase angle in g_m was not negligible. A phase-shift network could have been inserted in the feedback circuit to make the phase angle negligible, but it was not inserted because the phase angle becomes negligible if the drop across the circuit consisting of the resistor R_0 and the potential coil Z_c in series is used as the feedback voltage E_2. This connection depresses the effect of temperature rise in the coil only to the extent that it is masked out by the magnitude of R_0 then required, but it allows β to be a real quantity and simplifies making the small adjustments to the amplifier gain required when a standby wattmeter must be used. This latter feedback connection is the one adopted, and the temperature rise of the coil is made negligible by using an automatic-release on-off reversing switch to substitute the coil and the resistor R_0 for a dummy load of equal resistance only during the short interval required to read the instrument. This switching arrange-

* Similar expressions for variations with respect to μ can be derived.[2]

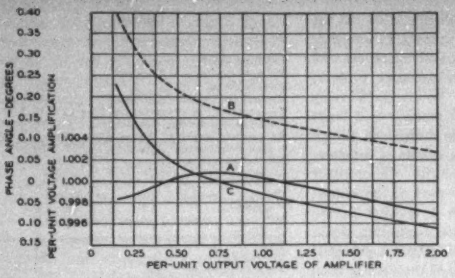


Figure 2. Characteristics of amplifier

Curve *A*—Per-unit voltage amplification

Curve *B*—Phase angle between input and output voltages

Curve *C*—Phase angle between input voltage and current in wattmeter potential coil

ment is also necessary to protect the coil against accidental burnout in the hands of operators of the network analyzer who might unknowingly overload it considerably for long periods.

The magnitude of the resistor R_0 necessary to mask the errors due to temperature rise in the coil to 0.5 per cent if operated continuously at normal working current, is about 450 ohms. This magnitude is used for the feedback resistor since it is not excessively large compared with that required to render negligible the effects of temperature rise in the remainder of the output circuit, and does not impose excessive burden on the amplifier. The wattmeter potential-circuit multiplier is used for the resistor R_0, by being tapped at a point which makes the coil resistance plus R_0 equal to 500 ohms. The amplifier output terminals are connected to this circuit, which represent a normal burden of approximately three watts at 40 volts.

The voltage amplification without the feedback and for the impedances shown in figure 1 is approximately 40. The negative feedback was increased deliberately to within a safe margin of the limit of stable operation of the system. This condition results in a net voltage amplification of about 2, and constrains the amplifier so that variations in its performance caused by changes occurring in tube characteristics are reduced to about five per cent of what they would be were no inverse feedback employed. For this over-all amplification, the voltage applied to the input of the amplifier is approximately 20 with normal current in the potential coil of the wattmeter. The cathode-bias resistors have no shunting capacitors because, if used, they introduce undesirable phase shift. The primary of the output transformer is tuned to reduce phase-shift caused by its exciting current.

The essential characteristics of the amplifier are indicated by the curves of figure 2. As seen from these curves the voltage amplification is essentially constant, and the phase angle between input voltage and potential-coil current is negligible throughout the operating range. Tubes of the same type having normal characteristics may be interchanged with a negligible change in performance. The instrument is ready to use within about one minute after applying voltage to its plate and filament circuits. The change in performance for a plus or minus four per cent change in voltage supplying the plate and filament circuits is negligible.

Input Networks

It is desirable to have the same wattmeter calibration and multiplying factors with the potential circuit supplied by the amplifier as with it supplied directly from the network. To give the desired multiplying factors for both watts and vars, two voltage-divider input networks are provided ahead of the amplifier, and each is adjusted so that approximately 20 volts is applied to the input of the amplifier when 100 volts is applied to the input terminals of either network. When the grid of the amplifier tube is connected to one input network, the current in the potential coil of the wattmeter is in phase with the voltage at the measuring point and allows the measurement of watts. When the grid of the amplifier tube is connected to the other input network, the current in the potential coil of the wattmeter leads the voltage at the measuring point by 90 degrees and allows the measurement of vars.

These input networks must impose a negligible burden upon the power-system network under study. To satisfy this condition, the criterion established was that their burden would be considered negligible if their magnitude was less than the magnitude of the uncertainty of the wattmeter reading. Thus, with a meter giving full-scale deflection for 60 watts and accurate to within one-fourth per cent of full scale, the burden imposed by the input networks of the amplifier should be less than 0.15 watt at 100 volts. The input network used to measure watts consists of wire-wound resistors, and imposes a burden of approximately 0.03 watt at 100 volts. The input network used to measure vars consists of resistances and capacitances and imposes a burden of 0.045 volt-amperes at 100 volts. The characteristics of this network are frequency sensitive; but, for the values of the circuit parameters, a change of one per cent in frequency changes the magnitude of the voltage applied to the amplifier by about one per cent and the phase-angle by about 0.2 degree. Since the frequency of the source varies less than ±0.2 per cent, the effect of frequency variations upon the characteristics of the phase-shift network is negligible.

The instrument is made to indicate either watts or vars by connecting the amplifier to the proper input network through a conveniently mounted switch. To extend the range of the instrument the grid of the amplifier tube is connected by another switch to different taps on the voltage-divider circuit as shown in figure 1. These provisions give the instrument a range from zero to 900 watts or vars.

In certain studies it has been found convenient to use one scale multiplier throughout a study, and to make the meter indication correspond directly to a convenient multiple of system base kilovolt-amperes by appropriate selection of analyzer base quantities. For example, if effective use of the analyzer equipment results when unit system kilovolt-amperes is 100,000, and unit analyzer volt-amperes is 400, the instrument reads system megavolt-amperes directly when the scale multiplier is four. Other convenient scale multipliers may be used.*

Calibration of the Instrument

Calibration of the amplifier-wattmeter combination instrument is accomplished readily. The wattmeter is first calibrated in the standardizing laboratory in the usual manner without regard to its ultimate use as part of the combination instrument. Then, when it is used as part of this instrument and its potential-coil current is supplied by the amplifier, the accuracy of the combination instrument is determined by comparing its indication

*H. P. St. Clair of the American Gas and Electric Service Corporation was the first to emphasize the value of this feature and as a result of his suggestions, the wattmeter dial has been graduated for zero to 24 as well as zero to 60 full scale to extend the applicability of this feature.

of a definite measurement with the indication of the same measurement given directly by the wattmeter when the appropriate tap on the potential circuit of the wattmeter is connected directly to the point of measurement. The voltage at the point of measurement must have the same value when each indication is read. The amplifier is made to have the desired amplification by adjustment of the tap connection on the resistance R of figure 1, which varies the feedback coefficient β. Because of the ease with which a check on the accuracy of the instrument can be performed it is done daily; but no readjustment of the feedback circuit has been found necessary during a ten-month period of use.

Application to the Measurement of Current

The instrument is useful to measure current rapidly in complex or polar form. To measure the in-phase and quadrature components of current the potential circuit of the amplifier is connected to an alternating-voltage source, preferably of 100 volts, whose phase angle may be regarded as the reference angle of the network under study. The current coil of the wattmeter is connected into a branch of the network. The instrument then indicates 100 times the in-phase and quadrature components of the current in this branch when the switch on the amplifier is connected to the "watts" and "vars" positions respectively. If the voltage is supplied by a phase-shifting transformer the angle of this voltage can readily be made any desired value.

To measure current in polar form, the switch on the amplifier is first connected to indicate vars. The phase-shifting transformer is then connected to the input circuit of the amplifier and the phase angle of its voltage adjusted until the wattmeter reads zero. The short time required for the pointer of the instrument to come to rest makes the operation a fairly rapid one. The voltage of the phase-shifting transformer is now in phase with the current in the current coil of the wattmeter. With the phase-shifter terminal voltage maintained at 100 volts, the instrument indicates 100 times the current when the switch on the amplifier is transferred to the "watts" position. The phase angle indicated by the phase-shifting transformer is the phase angle of this current with respect to the reference voltage of the phase-shifting transformer. The magnitude of the voltage is chosen as 100 while using this instrument to measure currents only to simplify the division of watts by volts to obtain amperes.

Conclusions

By employing a negative-feedback amplifier it has been possible to obtain an instrument using essentially stock parts which has the speed of indication of commercially-available portable instruments, and, at the same time, sufficiently low current-coil impedance and potential-circuit admittance that its burden is negligible compared with the quantities to be measured on the network analyzer. The instrument is accurate to better than one-half per cent of full scale for any range when indicating watts or vars. It is not unlikely that a device of this type has other important applications in the field of electrical measurements.

This instrument with associated equipment so expedites the metering procedure on the MIT network analyzer that the speed at which data can be reliably recorded controls primarily the time required for such a study. In addition, this equipment makes it practicable to include numerous refinements in the procedure employed when performing certain studies.

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Discussion

R. N. Slinger (General Electric Company, Schenectady, N. Y.): The authors of this paper are to be congratulated for their excellent work in making use of the negative-feedback amplifier circuit with a 60-cycle semistock portable wattmeter. While their primary objective was evidently to improve the speed and accuracy of their network analyzer instrument system they have perhaps also pointed the way to further fields of usefulness for precision type amplifiers of this type.

As they have indicated, the requirements for a wattmeter-amplifier combination suitable for application to a network analyzer are quite severe. Accuracy, speed of response, and extremely low instrument burden are all exceedingly important. The instrument combination also must be capable of retaining its calibration within close limits over relatively long periods of time and the indicating instrument must be of such form that it can be read easily and rapidly many times a day without undue eyestrain. In fact, almost the only common instrument requirement not included is the frequency-response characteristic, which is not of importance in this instance only because the analyzer reactor and capacitor circuit elements make a constant-frequency power source one of the essential components of a network analyzer.

Another important requirement not specifically mentioned in the paper is the ability to withstand frequent and severe momentary overloads. The range of currents that must be measured in the course of an average system study may easily be as great as 500 to 1. With magnitudes of the current and to a lesser extent the voltages, differing so widely, even the best of operators will occasionally inadvertently connect the instrument into circuits carrying several times the current or voltage they had expected, especially when the instrument is of a type specifically designed for high-speed operation.

It is not clear how the instrument described in this paper will be protected from serious overloads, particularly on low-power-factor readings, or how it will be arranged to cover a sufficiently wide range of currents. By proper design of the output characteristics of amplifiers for either current or potential circuits, they can be made to protect the instrument by limiting the maximum output to values that will not result in serious damage. It would be of interest to know how the authors have solved these problems.

They have indicated the convenient method in which the instrument lends itself to the measurement of components of current. It would seem equally important to be able to measure components of voltage as well. To do so, would necessitate connecting the current coil of the wattmeter to an adjustable power source to provide a reference current. The potential coil of the wattmeter could then be connected to the network at any desired point for the measurement of voltage components.

In the design of the input network, a slightly different arrangement of the constants might result in a better instrument working range. Most of the voltages in an analyzer representation of a power network will ordinarily fall within the range of 90 to 110 per cent of base voltage. Therefore, it might be better to design the input network to give a full-scale wattmeter deflection with 0.6 ampere in the current coil and 150 per cent of base voltage on the terminals of the input network. For load study readings this would ordinarily permit the use of only one potential-coil multiplier for all readings without danger of overloading the potential-coil circuit. The other multipliers for use in other types of studies could then be convenient multiples or fractions of this multiplier.

The authors' statement in regard to the interchangeability of tubes is quite in line

with experience obtained on the General Electric Company's network analyzer in Schenectady. This analyzer, using a similar circuit for the instrument amplifiers, as described in a paper presented at the winter convention a year ago, and using a light-beam type wattmeter constructed from conventional parts has now been in almost constant operation for a year and a half. The instruments have been periodically checked for calibration and some of the tubes in the amplifiers have been replaced as they showed signs of diminishing emission. However, no difficulty whatever has been experienced in operating the amplifier with some new tubes and some old ones and very little adjustment of any kind has been required since the instrument system was put into operation.

Eric A. Walker (Tufts College, Medford, Mass.): In the measurement of small amounts of power there is one source of error introduced by the wattmeter itself, which can be neglected only if certain precautions are taken to make this error as small as is possible. This error is one resulting from what might be called the transformer effect of the coils. The flux set up by the current coil of the meter generates a voltage in the voltage coil in addition to that impressed by the external circuit. This additional voltage causes an additional current in the voltage coil.

The same action takes place in the opposite direction: the current in the voltage coil causes a flux which gives rise to a current in the current coil. Both of these effects can be checked by energizing either the voltage or current coil in the proper manner and short-circuiting the other coil.

These two effects cause errors which are not constant but which are effected by a number of factors. These are: (1) the voltage impressed on the voltage coil; (2) the current flowing in the current coil; (3) the amount of coupling between the windings which changes with the position of the coils; (4) the impedance of the circuit connected to the voltage coil; (5) the impedance connected to the current coil.

As was said before, the error is not important in wattmeters designed for large amounts of power especially when the power factor is near unity. However, for wattmeters having a full-scale deflection of about five watts at power factors of 0.01 and below, the errors so introduced may be larger than the actual reading.

The difficulty may be overcome by arranging the circuits so that a high impedance is connected in series with both windings and the currents then caused by the transformer action are small.

W. O. Osbon (nonmember) and **W. W. Parker** (both of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors are to be congratulated for the thorough manner in which they have described the application and design of the amplifier-wattmeter combination for use with the MIT network analyzer. The paper contains data which will be interesting and useful to those concerned with both network calculators and negative-feedback amplifiers and their application.

The special interest in this paper results from the recent development of a negative-feedback amplifier but along somewhat different lines. This amplifier unit and associated instruments are shown in figure 1 of this discussion. Current feedback instead of voltage feedback is used which avoids difficulties and circuit complications due to heating of the instrument coils.

Without sacrificing quality of performance the amplifier assembly has been made very compact, being only 9 by 10 by 12 inches. It includes a power pack and two separate two-tube amplifiers, one for the voltmeter and the wattmeter voltage coil and the other for the ammeter and wattmeter current coil.

Due to the use of both current and voltage amplification it has been possible to use standard instruments as far as torque, speed of response, and damping is concerned.

The necessity for a large number of instrument readings in calculator studies makes it desirable to have direct readings to cover the range of values required for any one problem. This is done by using instruments which have two overlapping uniform scales. Direct readings are obtained of current, volts, watts, and vars without the necessity of multipliers for problems using the normal calculator voltage level. When the lower voltage level is used (primarily for short-circuit studies) the infrequent wattmeter readings are multiplied by 0.2, all other readings being direct. Phase angle and component quantities of currents and voltages are obtained on the "universal vectometer" which is used in conjunction with the amplified instruments. The "universal vectometer" has been previously described in the *Electric Journal* for May 1933.

G. S. Brown and **E. F. Cahoon:** The authors appreciate the many interesting points raised in the discussions by Messrs. Slinger, Osbon and Parker, and Walker.

Mr. Slinger's emphasis of the severe requirements imposed upon an instrument used in a network analyzer, and his mention of the experience obtained on the General Electric Company's analyzer in regard to the freedom from tube troubles, are much appreciated. In answer to Mr. Slinger's question concerning the protection of the instrument against serious overloads, we would like to mention again that the current coils of the wattmeter are essentially those used in a stock meter rated for five amperes. As stated in the paper, this relatively large rating results from the low-current-coil-impedance criterion imposed by the analyzer application. Since the parallel connection of the coils permits working up to ten amperes, and since no generator on the MIT analyzer is rated more than six amperes, the danger of burnout of the current coils is not great.

As for the potential circuit, a small overload-alarm device is connected in parallel with the dummy amplifier load, this device and the dummy load being connected to the amplifier except when a reading is being made. The alarm device was not described in the paper in order to save space. It consists briefly of a relay energized through a diode rectifier from the output of the amplifier. The relay operates a warning light whenever the output voltage is (1) large enough to endanger the wattmeter potential coil, or (2) more than the amplifier can supply without departure from the linearity or phase-angle requirements. The warning light is located adjacent to the key that is operated to substitute the potential-coil circuit for the dummy load, and hence is readily noticeable.

Again referring to Mr. Slinger's discussion, the potential coil taps on the input network are used principally to change the range of the instrument, and seldom to match with some particular voltage base. If our design had permitted a simple means to change the current sensitivity the suggestion of an input network adjusted for about 150 per cent normal voltage as maximum voltage, might have become a practical matter.

The point raised by Professor Walker is an extremely important one. It is rarely mentioned in discussions of instruments to measure watts or vars, perhaps because the total potential circuit and total current circuit impedances are relatively large in the conventional instrument applications. To demonstrate the importance of this point, the deflection of the pointer in the wattmeter of the instrument described is about one-tenth full scale when the *potential coil* is short-circuited and rated current is applied to the current coil. However, with the 450-ohm feedback resistor connected in series with the coil and the series combination short-circuited no deflection can be detected. Similarly, the pointer deflection is again about one-tenth full scale with normal potential-coil current applied and the *current coil* short-circuited, but with 0.5-ohm impedance in series with the current coil and the combination short-circuited, no deflection can be detected. Since the equivalent current-circuit impedance is usually in excess of 10 ohms, as discussed in the paper, the instrument is believed to be free from the transformer effect of the coils. However, the authors are glad that this point was raised, because they are aware of other attempts to build an instrument of the type described that were unsatisfactory because of the relatively large currents induced by the transformer effect.

Figure 1

Notes on Emergency Ratings

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MEMBER AIEE

COSTS of money, depreciation, and taxes now represent almost two-thirds of all electricity-supply costs. Other costs have been reduced to the point where it is difficult to effect further large reductions in them. It appears, therefore, that the major opportunities for improving the competitive position of electricity must now lie in the direction of lowering the fixed costs by reducing to a practical minimum the investment required to deliver adequate voltage and the nearest practicable approach to continuous power supply.

Increased load ratings may represent one logical step in the solution of this problem. Such a step requires primarily the reconsideration of emergency load conditions, since these alone have almost traditionally determined when additions to load-carrying plant should be made. There are so many phases and so many different types of apparatus to be considered in any general program for increased load ratings that it would be quite impossible, if it were the intent of this paper, to go beyond a simple discussion of a few pertinent relationships and to outline some thoughts that may be helpful to others also working on this problem.

Almost more frequently than for any other single element in the distribution system, it becomes necessary to determine the extent to which cable of some sort determines the load rating which may be applied. In their relation to the system plan, most of the load-rating problems are so nearly parallel to those for cables that a careful discussion from the point of view of the cable plant not only permits drawing upon a wealth of convenient illustrations but at the same time should be helpful to the engineer who faces a similar problem for other apparatus. Let us consider for a moment the place of emergency ratings in the system plan.

Place of Emergency Ratings in the System Plan

Economy in fixed charges can be attained in each of two directions. The first is to provide economically the capacity needed to carry the transient load occasioned from time to time in the normal course of events when a sub-station supply cable, transformer, or some other link in the supply system, fails in service. This sort of emergency is almost a routine affair, to the extent that it is usual practice to select a design which will meet such a situation with the minimum practical need to disturb the load being supplied under the conditions. The gradual extension of the network principle to points nearer the customer's service take-off simply extends the limits within which such failures of equipment may occur without causing a customer's service interruption. The value of the emergency rating in this case lies in permitting each link in the supply system to carry as high an average day load as is possible, without in any way reducing the ability of the system to meet such transient emergency loads. The duration of such emergencies may range from, say, 12 hours to locate and repair a cable fault, or 24 hours to replace a substation transformer bank, up to perhaps three months to repair a large transformer and return it to service if a spare unit is not available.

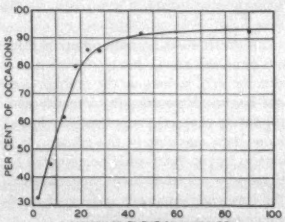

Figure 1. Per cent of occasions when alternate source is needed, versus their maximum duration

The second type of emergency includes the group of situations which accompany a major system disturbance. Under such conditions, the system operators may need to use every available supply link to the practical limit of its capacity, until it is possible to isolate the fault and return the load to its normal source of supply. Figure 1 summarizes for one system about 100 observations of the time during which it has been necessary to supply distribution substations from an alternative source, over emergency tie lines that are provided for such use while the normal source of supply is being restored to regular operation after a major disturbance. It will be seen from this that about 85 per cent of such cases require use of the alternative source for less than one-half hour. Hence, there may be occasional need for very high short-time emergency ratings. These may have little value for increasing the average daily loading of the normal supply elements of the system but will serve to reduce the extent of customer inconvenience to a minimum during a major system disturbance. It may even be helpful to have a one-hour and a two-hour as well as a one-half hour rating, so as to provide the utmost flexibility for redistribution of load, before it should be necessary to reduce loads to the lower permissible values for all-day emergency operation. One plan that has some attractive possibilities in operation of a supply cable system would permit following any one of the following emergency load schedules, in per cent of normal load:

(*a*). Two hundred per cent for one-half hour, followed by 130 per cent for the rest of the load cycle;

(*b*). One hundred sixty-five per cent for one hour, followed by 130 per cent for the rest of the load cycle;

(*c*). One hundred fifty per cent for two hours, followed by 130 per cent for the rest of the load cycle; or,

(*d*). One hundred thirty per cent for one complete load cycle.

Thus, the schedule to be followed in each given instance would be determined automatically by the magnitude of the initial load. Radial distribution feeders ordinarily may not require sufficient use of one-half hour or one-hour ratings to justify provision for them. However, the 150 per cent–130 per cent load schedule has the merit of providing time for load transfers in the field when this becomes necessary for the best redistribution of the emergency loads between the remaining circuits in an area affected by a service failure of one. This does not by any means exhaust the possibilities that will face the engineer in each of the wide variety of possible occasions for the use of emergency ratings. It does serve to

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The author is indebted to many writers on temperature, particularly to V. Karapetoff,[1] V. M. Montsinger,[2] Wallace B. Kirke,[3] Elwood A. Church,[4,5] and William H. McAdams,[6] whose works were most helpful. He is especially grateful to his associates for their contribution to such of his observations as may prove to have value.

1. For all numbered references, see list at end of paper.

illustrate the occasional needs for meeting both short and comparatively long-time emergency load situations.

Perhaps the most important principle to be kept in mind in the consideration of emergency ratings is that the maximum emergency loads to be carried should not affect the ability of the system to operate satisfactorily under such extreme conditions, or be sufficiently severe, with due regard to their probable magnitudes and frequency of occurrence, to cause an unreasonable reduction in the average life expectancy of the facilities required to carry such loads.

Economy alone may often urge even more severe treatment of the cables and other load-carrying equipment than would be acceptable if its attainment should require measurable sacrifice in safety, dependability, or flexibility. The underground substation supply cable in a metropolitan system, for instance, may represent no more than 30 per cent of the total installed cost of line switching sections, useful duct space, manholes, and cables. It may be good business, therefore, to take advantage of an appreciable increase in average load per cable at the expense of a possible corresponding increase in cable maintenance costs. In many respects the situation is quite the same for substation equipment, etc. Decision as to the practical limit of this economy naturally requires consideration of all the factors in the light of experience and seasoned judgment. In appropriate circumstances, however, an above-average failure rate may represent more careful engineering than would a low failure rate.

The Magnitude of Emergency Loads

One of the facts that appears to be most confusing to those charged with direct responsibility for cable or apparatus ratings in electricity distribution is the usually very low average ratio of peak load to installed capacity. Surveys often show, for instance, that the average load per cable at the time of maximum station output is less than 70 per cent of its all-day emergency rating. Two factors, service continuity and load growth, almost entirely explain this difference between installed capacity and the average yearly peak load per cable. Nearly all additions to distribution plant investment are made to provide for the supply of load growth and to maintain, or improve, service continuity. Perhaps it would be helpful to illustrate the effect of these two factors by discussing their effect upon substation supply cable loading.

Let us assume that the load on a substation in one year is just equal to the normal load capacity of two supply cables. Also assume, tentatively, that the emergency and normal load ratings are identical for these cables, so that a third cable has been provided in order to have two cables available, should one fail. In the following year, however, a small increment of load growth requires the installation of another cable and, in that year, four cables are needed to supply but little more than a two-cable load. Load growth will then gradually absorb the spare capacity, until a time is reached when the load on the substation will very nearly equal the capacity of three cables. During the interval between the installation of the fourth cable and the time when its capacity is required for adequate reserve alone, then, there has been an average excess of installed cable capacity above load that is about equal to the capacity of $1^1/_2$ cables. Stated in more general terms, this amounts to saying that any substation which has a growing load and is supplied by n cables will have an average of 1.5 cables excess above load hence the average ratio U of total installed emergency load capacity to the yearly maximum demand on the substation would be:

$$U = \frac{n}{n - 1.5} \qquad (1)$$

This ratio holds for any group of three or more identical lines, transformers, circuits, etc., so long as the number does not become large enough to justify consideration of coincident emergency loss of more than one unit in the group. It is always larger than would be expected by those who are much more accustomed to the lower instantaneous ratio u of emergency to normal loads:

$$u = \frac{n}{n - 1} \qquad (2)$$

Few substations are supplied by more than seven lines or have more than four transformer banks and some have only two. While it is true that the number of primary distribution circuits is large, it is seldom that the load of one circuit can be transferred to more than three adjacent circuits if it should fail ($n = 4$) and, similarly, it is often impractical to transfer the load of one distribution transformer to more than two adjacent transformers ($n = 3$). Hence, in each part of the distribution system, we find we are dealing with groups of units in which the values of (n) range from 2 to about 7. By substituting such values in equation 1, we may find directly that the resulting ratio of emergency load rating to the average yearly maximum demand per unit (table I) ranges from 4 to 1.27 for each such group. The corresponding values of the instantaneous ratio u are also shown.

Table I

Number of Units Normally in Service	Average Ratio (U) Emergency Load Rating to Average Yearly Maximum Demand per Unit	Instantaneous Ratio (u) of Emergency to Normal Load
2	2 to 4.0*	2.00
3	2.0	1.50
4	1.60	1.33
5	1.43	1.25
6	1.33	1.20
7	1.27	1.17

* Note: Formula not entirely satisfactory for this case.

Thus, there may be many substation supply cables in a given underground duct bank but, if the average number of supply cables per substation is four, the sum of the normal noncoincident maximum demands on all the supply cables in that duct bank probably will not reach a total greater than 62.5 per cent (100 per cent/1.6) of the combined emergency load ratings of those same cables. The same general relationship operates inexorably for each other class of load-carrying equipment in a growing distribution system and, to some less extent, in the bulk-power system.

It is possible that economy in load-carrying facilities may be improved to some extent, however, by judicious application of emergency load ratings that are somewhat higher than the load ratings which would represent sound engineering practice for regular daily operation. Equation 1 is also helpful in illustrating the maximum ratio of emergency to normal load ratings which would be required in order to bring the average yearly maximum demand up to a value equal to the installed normal load rating of each group of two or more units normally in service. Higher ratios have no practical value. Ratios as high as 1.6 and 2.0 would represent hopeless requirements, however, if emergency loads and their effects upon operating temperatures did not differ materially from normal load conditions.

We may, therefore, conclude from the foregoing discussion that the average cable loading and load losses in any given duct run are materially lower than might be expected if load growth and the usual provisions for continuous supply were not present. The emergency load losses lie in the range of 1.4 to 4.0 times the normal load losses, or in such a relative magnitude as to require special consideration. Further, the severity of the all-day emergency load occasioned by failures of

load-supply elements in service decreases materially as to the number of elements per group increases. Hence, the need for high emergency ratings practically disappears as the number of cables exceeds five or six per substation.

An ordinarily practical engineering approach to increased load ratings would be to determine first what maximum normal load rating may be permitted under the circumstances, then consider whether the probable emergency-load transients will be sufficiently frequent or severe to require that they, rather than the normal load conditions, determine the need for installing additional capacity. Emergency operations differ from normal conditions chiefly in two respects:

1. Emergency loads are transient in nature and, usually, short lived.

2. The probability is usually very remote that an emergency will occur at the time when loads, ambients, and the limitations of installed capacity would combine to require operation of the equipment at the highest possible temperature which is selected as the design limit.

Nearly all loads are variable in their nature rather than constant. Hence, the maximum temperature reached lasts for a very short time and is in most cases considerably lower than would obtain if the usually appreciable thermal capacity of the apparatus were not present to reduce the temperature changes that accompany changes in load.

The problem of emergency load ratings, therefore, reduces to consideration of such factors as the operating temperatures to be expected and their possible relative effect upon the life of the apparatus in question, as determined not only by the temperature-life characteristics of the apparatus, but also the probability of occurrence of transient loads sufficient in magnitude to require operation at above rated temperatures, or with abnormal voltage regulation.

Approximate Frequency of Cable Failures in Service

Perhaps to a greater extent than for any other equipment, the cable engineer has access to a sufficient volume of data to determine with reasonable assurance the probable failure rate for any cable or group of cables. There are, for instance, about 15 cable sections and joints per mile of an underground cable installation, within which distance there may be exposure to a wide variety of conditions such as hot spots, electrolysis, water, abrasion, bending, etc. Relatively few miles of such construction are therefore needed to give the law of averages a reasonably good chance to work.

In any given system, the deviations from the average failure rate usually may be explained. The author is familiar with an instance in which 22 miles of 13.2 kv cable were recently operated for about three years at very nearly twice the former average daily load and at maximum conductor temperatures ranging from 90 to 105 degrees centigrade. The failure rate averaged $4^1/_2$ times the prior ten-year average for this cable, but the station economies made possible by such extraordinary operation far outweighed the increased cost of cable maintenance. By far the chief causes of cable failure in this instance were sheath cracks at cable bends in the manholes or sheath abrasion over rough spots in the duct, both of which were due to the longitudinal movement of the cable. Only one failure occurred in a section of cable that showed definite signs of insulation injury by the inordinately continued repetition of high-temperature operation. There are no doubt other such cable sections that have not come to light and might ultimately accelerate the failure rate but the usual sheath crack was the direct cause of this failure. From these observations there is some indication that, for less severe conditions, the cable failure rate should be expected to increase almost in direct proportion to the thermal movement of the cable, or in proportion to the square of the load carried.

We can now estimate roughly the probable failure rate for cables supplying a given substation. Consider a group of five parallel supply cables, operating regularly at 80 per cent of their combined normal load rating, in which a cable failure may be expected about once in 450 load cycles. If the load were allowed to increase until the five cables would operate regularly at 100 per cent of their normal load rating, the average failure rate due to normal load operation might increase to about $(100/80)^3$ times the previous rate, or one in 290 load cycles. Should a failure then require operation over one load cycle in 290, at a failure rate that is ten times as severe as for the average normal load cycle, the over-all failure rate might further increase to one in 280 load cycles. In such an instance, the chief cause of the increased failure rate, therefore, would appear to be the increased normal loads and temperatures.

Similar analyses in respect to other types of equipment apparently develop similar results. In some cases it may be well to recognize the appreciable life loss due to all causes other than temperature, such as obsolescence, natural old age, mechanical damage, etc. In some instances this may be found to contribute as much to the average rate of life loss as do normal load temperatures. If the magnitude of this factor can be judged, its effect upon the existing rate of life loss should be deducted before estimating the change in life loss chargeable to a change in operating temperatures.

Distribution Load Characteristics

Seldom in the distribution system does the load correspond to the conditions which determine the name-plate rating of the load-carrying apparatus, or the conditions often assumed in establishing load ratings for cables. In some respects questions of seasonal load variations, as well as the daily load changes, involve conditions so complex that it is almost impossible to subject this phase of the problem to rigid analysis. Furthermore, the present growth of electric-range, off-peak, and air-conditioning load introduces factors which have a profound influence upon the shape of the daily load cycle. The development of such loads already has reached the point where the load curve at one location in the distribution system may bear very little direct relationship to that at another. It is no longer possible to select a load cycle that may be said with assurance to be typical or representative of any location except that where it was encountered. This becomes increasingly evident in the smaller supply units of the distribution system, such as substation circuits, distribution transformers, and low-voltage circuits where nearly all degrees of relative saturation of these new loads already exist.

To some extent, however, the range of load variation in a given case may be judged from load curves such as in figure 2*a* for all-day loads, or in figure 2*b* for short-time loads. These illustrate respectively the distribution of normal daily maximum demands and hourly loads throughout the year on one substation. All extraordinary loads were excluded from the data used in their preparation. Substations having identical load factors may have different load curves, although the area under the solid curve of figure 2*b* is proportional to annual load factor. Such curves become quite helpful for use in analyses to determine the approximate probability of meeting given load, voltage, or temperature conditions. The dotted curves shown in these figures illustrate the corresponding loads at each of five levels while the yearly maximum demand is growing, say, from 80 per cent

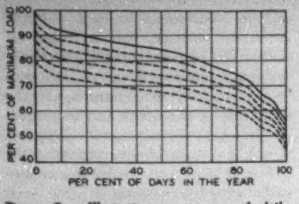

Figure 2a. Illustrative occurrence of daily maximum demands on supply cables, for yearly peak loads ranging from 80 per cent to 100 per cent of normal load rating

to 100 per cent of the installed load rating in a given case.

Approximate Probability of Emergency Load Occurrence

The probability of load occurrence is one of the most important factors in consideration of emergency ratings. Three truths must be appreciated in dealing with this factor, however. First, the necessity for dealing with averages makes the conclusion no better than the average from which it is derived. Second, an occurrence that may be expected no oftener than once in 100 years may confront the calculator within a month. Third, a loading condition which may be expected only once in 25 years in a given group of cables will be faced on an average of twice a year in a system which has 50 such groups of cables. These, however, serve only to emphasize the importance of selecting design limits for emergency operation that are no higher than the proponent is willing to face.

One use of probability will now be illustrated by a sample calculation for five cables supplying a distribution substation. For example, assume a supply-cable failure may be expected on an average of 1.4 times per year and that five years is required for the peak load on that substation to increase from 80 per cent to 100 per cent of the normal peak load capacity on all five cables. To be satisfied with such a design, the engineer must be willing to face the possible need for carrying an emergency load that can reach a maximum of 1.25 times the normal load design limit, should one cable be out of service at the time of the peak in the last year. Let us assume this is reasonable, and calculate the probability that an all-day outage of one cable would require the others to carry a peak load as high as 1.10 times their normal load rating. This will occur whenever the load on the substation would exceed 88 per cent of the total installed normal load rating of the five cables. By reference to curves such as shown in figure 2a, it may be found that the normal daily maximum demand in this instance will not exceed 88 per cent of rating at any time during the first or second years, but will during 3.2 per cent of the third year, 11.2 per cent of the fourth year, and 28.5 per cent of the fifth year, or an average of 8.58 per cent per year. With 1.4 cable failures per year uniformly distributed, then, the probability of cable failures during daily load cycles whose normal maximum loads exceed 88 per cent of rating becomes 0.0858 times 1.4 or 0.120. In this instance, then, all-day cable outages might be expected to require the remaining cables to operate at loads above 110 per cent of normal load rating on an average of once in about eight years. Other points may be calculated similarly and have been shown in the lower curve of figure 3. Should one-half day be ample to repair a cable fault, the corresponding time intervals for this curve would double.

For short-time emergencies the method of calculation is about the same as for the case just illustrated and may give a result quite like the dotted curve of figure 3. However, if figure 1 should represent the probable duration of such short-time emergencies, it is apparent that only one in seven will last as long as one-half hour. Hence, the probable interval between occurrence of loads requiring one-half hour or longer operation at the given or a greater load becomes seven times as long as the probable interval between the short-time emergencies. This latter relationship is also shown in figure 3.

As earlier pointed out, such calculations should not be used as a basis for making close decisions. These calculations, for instance, do not recognize the certainty that unbalance of loads between cables may load some heavier than others, etc. However, such curves become quite helpful in judging the maximum amount of life loss which is reasonable to accept, in selecting the design limits for emergency and normal load ratings. In the instance just used for illustration, the author considers the emergency-load design limits sufficiently conservative to permit their use as often as once each year, without any apparent effect upon cable maintenance costs and without any ominous increase in the likelihood of such operation causing a second cable failure during such a state of emergency.

The foregoing discussion can serve only to point out some of the factors which work together to make the probability of severe loads and temperatures much more remote than the apparatus engineer is apt to realize. Variations in the rate of load growth seem not to have an important effect upon the answer. Neither is it necessary to have an accurate knowledge of the failure rate since variations in the range of two to one can only halve the number of years between the occurrence of a given or higher load. In any event it is apparent that the probability of severe loading conditions is quite remote.

Since the major purpose of emergency ratings is to permit increasing the average-day loading of the load-carrying elements in the system and this may increase voltage regulation, as well as operating temperatures, it becomes necessary to give some passing thought to voltage.

Voltage Regulation

Voltage regulators can be made to take care of increased regulation elsewhere and, with present available methods, can also reduce the spread between the first and last customers on the circuit. Small fixed boosters, shunt capacitors, and step-type regulators are now available for use by those who find that increased load ratings introduce normal-voltage regulation problems that cannot be solved as well by orthodox copper addition or rearrangement.

With the gradual extension of some form of the network principle beyond the substation bus and farther out into the distribution system, emergency voltage regulation, however, becomes one of increasing importance. This is particularly true of aerial distribution. It is the more urgent because the number of parallel paths normally available for the supply of the load in this part of the system often is as few as two, hence the instantaneous ratio of emergency to normal load approaches values as high as 2.00.

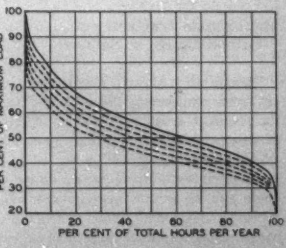

Figure 2b. Illustrative substation supply-cable load duration, for peak loads ranging from 80 per cent to 100 per cent of normal load rating

The principal gain possible by "networking" is its contribution to increased service continuity. This, however, is a voltage problem in its own right, since service discontinuity is the simple case of no voltage at all. To illustrate further, let us assume that there are two circuits supplying adjacent areas with voltages which lie outside the established limits of normal voltage variation only when one of the circuits fails to deliver any voltage at all, while trouble-men labor to clear the fault. By suitably "networking" these two circuits it may be possible to make the "no voltage" occasions much less frequent. The cost may well be unreasonable, if not almost prohibitive, however, should the design be made sufficiently rigid to prevent any possibility of ever delivering to the last customer a supply voltage that lies outside the accepted limits for normal operation.

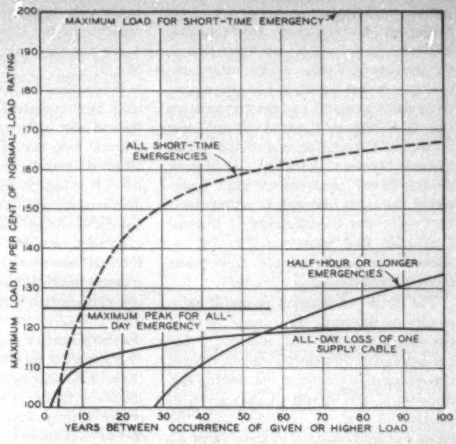

Figure 3. Approximate probability of load occurrence for five cables supplying one substation

This raises the rather natural question whether it may not be good business to improve service continuity just so long as no step thus taken will result in delivering to the last customer less voltage than he needs to permit his refrigerator motor to start; should its thermostat call for power in the rare instance where none would be available if the network had not been provided to supply no less than the bare necessities, until conditions can be restored to normal. The probability that apparatus failures will conspire with loads to precipitate such a situation, during the hour or less required to clear the fault in such instances, may be determined without much difficulty, as for figure 3. Thus, this phase of emergency ratings would appear to suggest the occasional need for considering some design limits for emergency voltage regulation that may be quite apart from those for normal operation. As in temperature considerations, it may often be found that conditions necessary to satisfy the normal voltage requirements will need no assistance to keep utilization equipment operating in the rare instance when an emergency may cause temporarily abnormal voltage regulation at some extreme locations.

Temperature Transients

Contrary to the author's expectations, when he approached the emergency-rating problem several years ago, it has become increasingly evident that the probable interval between occasions when it would be necessary to operate at high emergency temperatures is often so long that the question of whether such an operation would cause 10 or 300 times the normal rate of life loss for the day in which it should occur reduces to one of comparative unimportance. Even as high a rate as 300 times normal life loss over one load cycle may be no more severe than one year of normal operation. Montsinger's evidence[2] that insulation life loss may in some cases double for each 8-degree-centigrade increase in temperature, however, seems to be sufficient to indicate that temperature calculations used as the basis for emergency ratings may occasionally require a practical answer that lies somewhere within 10 degrees or 20 degrees centigrade of the actual. The accumulation of sufficient data in practical operation to indicate which of the present theories of life loss is best may require some time. It will require reasonably accurate knowledge of the temperatures responsible for that life loss.

Published methods for direct calculation of operating temperatures for cables, transformers, etc., are available. Mathematical analysis, however, can give no better answer than is permitted by the accuracy with which the various thermal coefficients and temperature corrections are known. These often cannot be evaluated deductively without disquieting assumptions and considerable labor. Hence there appears to be some need for a little better general understanding of means which permit the engineer to determine empirically from test or other available data, all the coefficients needed to estimate the thermal response of the assembly in question to any regular or irregular transient load impulse. This can be accomplished by the use of an equivalent circuit which is not materially different from that usually assumed in calculations of steady-state load temperatures. Since load transients require consideration of copper losses only, it is helpful to treat the hot-spot temperature θ in two components:

1. The constant component or "threshold temperature" T_0 which is the sum of the ambient temperature and the steady-state temperature rise caused by such factors as no-load losses and that part of the copper-temperature rise which corresponds to the average daily copper losses of the cable itself and its associates in the given conduit run.
2. The variable component θ_1 caused by the instantaneous difference p between the impressed copper losses and those copper losses, if any, which contribute to the "threshold temperature."

The "threshold temperature" component may be developed exactly as the calculator has been in the habit of estimating normal-load temperatures. This method of approach makes it necessary to know the transient load characteristic of the assembly for a total period equal only to the maximum probable duration of the emergency. There is seldom need to deal with transients which persist longer than one day.

Now, let us consider the thermal circuit for the dissipation of the copper (variable) losses through the various successive steps encountered in the transfer of these losses from the conductor out to ambient. In a cable installation, for instance, there is a series of successive steps, such as copper, insulation, sheath, etc., which can be represented by the electric-circuit analogy of figure 4. This approaches an exact representation, as the steps become smaller. In this circuit the thermal dissi-

pation coefficients s_{12}, s_{23}, . . . , s_n are analogous to electrical conductances, while k_1, k_2, . . . , k_n are analogous to electrical capacitances. The instantaneous copper-loss input p has the nature of an electric current and the temperature rise θ_1 is the resultant "voltage" rise needed at the sending end of the circuit to cause "current" p to flow. As in most electric circuit analyses we shall tentatively disregard the effects of temperature upon the s coefficients of thermal dissipation and upon the electrical resistance component of the copper loss input p.

The circuit of figure 4 is useful principally to illustrate the general form of the natural response to an impulse. From his familiarity with electric-circuit theory, the reader may recognize the sending end response of this circuit as that given in equation 3, for the condition that the input p is held constant at some value P:

$$\theta_1 = AP(1 - \epsilon^{-at}) + BP(1 - \epsilon^{-bt}) + \ldots + NP(1 - \epsilon^{-nt}) \quad (3)$$

Those who do not recognize this response may observe the development of that for a "two-chunk" circuit, in appendix B. Theoretically, each additional step in the circuit of figure 4 will require an additional term in equation 3. Where there are many steps, or the circuit constants are distributed rather than lumped, it is often necessary to use some mathematical expedient to evaluate equation 3. In his analysis of radial heat flow, for instance, Church[4] has shown how it is possible to obtain an expression for the harmonic impedance function for each homogenous step in the thermal circuit and, from these

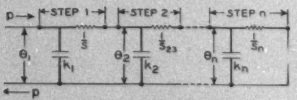

Figure 4. Thermal circuit

data, to determine the position of each of several points along the rectangular impulse characteristic. He has used a method so powerful that it can digest nearly any combination of steady-state harmonic functions that will represent the circuit at hand, and will produce the numerical position of any desired point along the curve of its response to a rectangular impulse. This method of harmonic analysis gets the answer, one point at a time, but seldom gives the response directly in its natural algebraic form. By whatever expedient the various points are evaluated, however, the characteristic response of the thermal circuit in figure 4 has the algebraic form given in equation 3.

It has been known for some time that only two exponential terms are needed to represent quite accurately the over-all thermal response of all the parts in an oil-filled transformer assembly. Similarly, it is known that aerial conductors, disconnects, and other assemblies whose current-carrying parts are sufficiently exposed to ambient temperatures, have thermal responses that may be quite accurately represented by the use of only one exponential term. Consequently, it does not seem to require undue use of the imagination to conclude that the form of equation 3 may be found to represent the natural heating characteristic for any situation to be encountered in electric power distribution. In any event, it should be possible to judge approximately the extent to which this is true throughout the range of a given set of observations. Let us now consider briefly the manner in which as few as two equivalent parts of such a circuit may be made to represent the infinite series of figure 4 and the following simpler equation:

$$\gamma = \theta_1/P = A(1 - \epsilon^{-at}) + B(1 - \epsilon^{-bt}) \quad (4)$$

In appendix A there is developed a method for determining the effective values of the parameters A, a, B, and b, which will make equation 4 approximately fit any group of test observations for a given rectangular load impulse. In table II are shown the values of the parameters used in plotting the four curves drawn in figure 7, for underground cables. The curves are drawn to show the loci of equation 4 with respect to the observed points, also shown for comparison along the heating characteristics. In this case the observations shown were calculated by Church's method (AIEE TRANSACTIONS for 1931, page 982, and for 1935, page 1166) as modified to recognize some additional features to which the author's discussion of Church's latter paper called attention (AIEE TRANSACTIONS for 1936, page 398).

Such faithful correlation, in figure 7, for the difficult case of the underground cable, has led the author to conclude that equation 4 can represent the rectangular load impulse characteristic of any assembly, for periods up to 24 hours duration, with sufficient practical accuracy to leave little need for rigorous analysis when suitable test data are available or can be obtained. If this is true, there is promise for considerably simplifying calculations of the emergency temperature transients

Table II. Equivalent Thermal Circuit Constants for 13.2-Kv Three-Conductor 350,000-Circular-Mil Cable in an Underground Duct Bank

	Hottest of Eight Equally Loaded Cables		Hottest of Two Equally Loaded Cables	
	Cables Dry	Cables in Water	Cables Dry	Cables in Water
1. Empirical circuit constants (Appendix A)				
A	7.48	3.52	7.00	3.56
B	12.9	13.7	10.4	5.92
a	0.819	2.08	0.857	2.07
b	0.118	0.0304	0.136	0.0480
2. Approximate circuit constants (Appendix B)				
K_1	0.132	0.130	0.133	0.130
S_{12}	0.090	0.256	0.096	0.260
K_2	0.763	2.34	0.884	3.58
S_2	0.108	0.0753	0.143	0.178

which accompany other than rectangular load impulses.

The approximate circuit of figure 5 most nearly corresponds to the actual thermal circuit, but has no particular advantage over the empirical circuit of figure 6 which has about the simplest arrangement of thermal capacities and resistances that will give exactly the same sending-end response to all regular or irregular impulses. The coefficients for the empirical circuit of figure 6 are known immediately

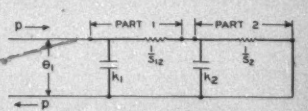

Figure 5. Approximate circuit

upon finding the parameters which make equation 4 fit the observed data, as by the method of appendix A. An advantage of the empirical circuit lies in the fact that the instantaneous input is the same for the A part as for the B part, while the instantaneous response of the A part is absolutely independent of that for the B part, so that:

$$\theta_1 = \theta_a + \theta_b \quad (5)$$

while,

$$\Delta\theta_a = (apA - a\theta_a)\,\Delta t \quad (6)$$

and,

$$\Delta\theta_b = (bpB - b\theta_b)\,\Delta t \quad (7)$$

For those who are sufficiently interested, appendix B gives the corresponding instantaneous relationships found in the approximate circuit of figure 5, as well as the relations between the equivalent thermal constants of this circuit and the parameters of the empirical circuit which has an identical response to all

transients. The following relations are included:

$$K_1 = \frac{1}{aA + bB} \tag{8}$$

$$S_{12} = K_1(a + b) - K_1^2 ab(A + B) \tag{9}$$

$$S_2 = \frac{S_{12}}{S_{12}(A + B) - 1} \tag{10}$$

$$K_2 = \frac{S_{12}S_2}{abK_1} \tag{11}$$

The calculator need know no more about the thermal characteristics of the assembly. Should he desire, he may now develop the approximate harmonic impedance function directly from figure 6, by analogy to the electric circuit of parallel resistance and capacitance. For instance, let $X_a = aA/\omega$ and $X_b = bB/\omega$, where ω equals $2\pi f$ radians per hour. Then the impedance $\boldsymbol{Z}$ of the empirical circuit becomes:

$$\boldsymbol{Z} = -j\left[\frac{AX_a}{A - jX_a} + \frac{BX_b}{B - jX_b}\right]$$

$$= \left[\frac{AX_a^2}{A^2 + X_a^2} + \frac{BX_b^2}{B^2 + X_b^2}\right] - j\left[\frac{A^2X_a}{A^2 + X_a^2} + \frac{B^2X_b}{B^2 + X_b^2}\right] \tag{12}$$

However, equations 6 and 7 offer means for a simple and direct tabular calculation that avoids any need for dealing with complex numbers or breaking the instantaneous values of p down into the various harmonic components. For instance, assume that: $B = 24$ degrees centigrade ultimate rise due to rated-load copper losses, while $b = 0.24$ and that it is desired to calculate $\Delta\theta_b$ for quarter-hour intervals ($\Delta t = 0.25$ hour). Substituting these values in equation 7 gives the following guide for calculating the approximate temperature change across resistance B during each quarter-hour interval:

$$\Delta\theta_b = 1.43p - 0.060\theta_b \tag{7a}$$

Table III shows a sample calculation for one illustrative load cycle, for which the load value at the beginning of each interval has been expressed in terms of the ratio R of load to rating. In instances where the "threshold temperature" does not need to include any part of the copper losses, it is often convenient to express the instantaneous load values in times rating R since this method gives the maximum temperature rise directly in terms of rating. The effects of temperature upon the values of p or the coefficients of the thermal circuit seldom have any practical importance in such calculations, so long as the parameters of equation 4 are based upon observations at constant load throughout the range of temperature changes within which it is desired to operate. The parameters then include the average temperature correction. The tabular calculation of θ_a may be made exactly as that for θ_b. Their maxima will not be coincident, but questions of such time-phase displacement take care of themselves. The fact that neither θ_a nor θ_b has any practical significance if taken alone, is of no disadvantage. The algebraic sum of their instantaneous values is always equal to the hot-spot rise θ_1 above the "threshold temperature" T_0. When dealing with cable-temperature calculations, in which the instantaneous value of p equals the total copper losses less the average daily copper losses in that cable, the values of p will be negative whenever the total copper losses fall below the average daily copper losses, if the calculator should elect to investigate temperatures during light-load periods. This method, however, makes it usually not necessary to start tabular calculation at a time when the copper losses are less than the average for a normal day.

Table III. A Sample Calculation Using Equation 7a as a Guide

Time (t)	Load (r) in Times Rating	1.43 p (1.43 r^2)	$-0.060\,\theta_b$	$\Delta\theta_b$	θ_b	
4:00 p.m.	0.34 R	0.167 R^2	−0.167 R^2	0*	2.78 R^2	
4:15	0.55 R	0.432 R^2	−0.167 R^2	0.27 R^2	3.05 R^2	
4:30	0.57 R	0.465 R^2	−0.183 R^2	0.28 R^2	3.33 R^2	
4:45	0.69 R	0.682 R^2	−0.200 R^2	0.48 R^2	3.81 R^2	
5:00	0.71 R	0.720 R^2	−0.228 R^2	0.49 R^2	4.30 R^2	
5:15	0.74 R	0.785 R^2	−0.258 R^2	0.53 R^2	4.83 R^2	
5:30	0.86 R	1.06 R^2	−0.290 R^2	0.77 R^2	5.60 R^2	
5:45	0.95 R	1.29 R^2	−0.34 R^2	0.95 R^2	6.55 R^2	
6:00	1.00 R	1.43 R^2	−0.39 R^2	1.04 R^2	7.59 R^2	
6:15	0.99 R	1.40 R^2	−0.46 R^2	0.94 R^2	8.53 R^2	
6:30	0.92 R	1.21 R^2	−0.51 R^2	0.70 R^2	9.23 R^2	
6:45	0.95 R	1.29 R^2	−0.55 R^2	0.74 R^2	9.97 R^2	
7:00	0.89 R	1.13 R^2	−0.60 R^2	0.53 R^2	10.50 R^2	
7:15	0.82 R	0.960 R^2	−0.630 R^2	0.33 R^2	10.83 R^2	
7:30	0.82 R	0.960 R^2	−0.650 R^2	0.31 R^2	11.14 R^2	
7:45	0.80 R	0.918 R^2	−0.668 R^2	0.25 R^2	11.39 R^2	
8:00	0.83 R	0.985 R^2	−0.684 R^2	0.30 R^2	11.69 R^2	
8:15	0.71 R	0.720 R^2	−0.700 R^2	0.02 R^2	11.71 R^2	
8:30	0.74 R	0.785 R^2	−0.705 R^2	0.08 R^2	11.79 R^2	maximum
8:45	0.68 R	0.660 R^2	−0.71 R^2	−0.05 R^2	11.74 R^2	
9:00	0.62 R	0.550 R^2	−0.70 R^2	−0.15 R^2	11.59 R^2	

* Note: This is often a safe assumption, if load changes are small prior to the period under observation.

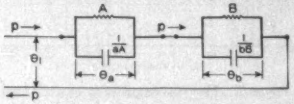

Figure 6. Empirical circuit

The time interval Δt that is used in equations 6 and 7 for practical calculations of cable temperature, seldom needs to be less than one-fourth to one-half hour, depending chiefly upon the number of observations of p that are needed to give a fair representation of the variations in copper losses. Adequate recognition of the thermal circuit itself is apparently retained so long as the interval Δt thus selected is not much larger than $(A + B)/4(aA + bB)$. When the value of a is large and a/b is greater than nine as for many transformers, however, it is readily possible that a more convenient value of Δt will make $a\Delta t$ greater than three. When this is true θ_a from equation 6 will so nearly reach its ultimate value pA within each step as to permit assuming this simplification of equation 6, and using fewer steps.

While the foregoing method appears to be direct and convenient for transient-temperature calculations, it is only one of several. It has been helpful to the author, in occasional difficult situations and has been outlined with the thought it may be helpful to others who are not already familiar with a method that produces satisfactory results. Many time-saving opportunities will appear to the calculator, as he becomes more familiar with the method he elects to use.

A possible use of the circuits of figures 5 and 6 for underground cables lies in the ease with which they permit a direct though somewhat approximate estimate of what would be the corresponding thermal circuit for some other size or type of cable in the same situation. An inkling of this possibility may be had from table II in which it will be observed that K_1 has the same value in each of the four situations, where S_{12} changes only with the addition of water in the duct. For underground installations, therefore, part 1 appears to be the cable itself. The per-

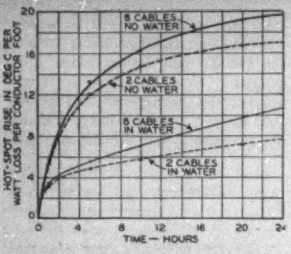

Figure 7. Hot-spot response to constant load losses, for groups of equally loaded 13.2-kv three-conductor 350,000-circular-mil cables in duct

centage change in the thermal capacity coefficient of the cable, also the corresponding percentage change in thermal conductance from copper out through the sheath, may be estimated in a few minutes. The effect of these changes in K_1 and S_{12} upon the parameters a, b, A, and B, may then be determined (appendix B) with almost the same confidence as though the original observations represented such cable.

A Word About Tests and Thermal Corrections

There are a few points regarding tests and thermal corrections that may be worthy of passing mention. Until one becomes thoroughly familiar with his data, it is usually best to express input in watts, thermal capacity in watt-hours per degree centigrade, thermal dissipation in watts per degree centigrade, and temperature rise in degrees centigrade per watt. Otherwise the test observations of rising temperature at constant load will appear to give a slightly faster moving response than similar observations after the load is removed. This is because of the greater acceleration caused by the effect of thermal increases in electrical resistance upon input in the former case. When using test data expressed in such units, there can be no confusion as to when to make some approximate final adjustment for the higher electrical resistance at the higher temperature. If the correction is excluded from the test data, it should be recognized in the calculation.

Where the hot-spot temperature cannot be read directly during a test on a given installation, the average copper temperature may be assumed to equal the hot spot, with sufficient accuracy for cable-temperature analyses. In oil-filled transformers, the hot-spot temperature at any time should be about equal to the average winding temperature plus the oil temperature rise from that at a level opposite the midpoint of the winding to that of the top oil. Thus it is usually possible to determine the approximate hot-spot temperature at each point of the test curve for cases where it cannot be read directly. It is seldom necessary to test any one assembly at more than one constant load value. If observations are taken on the heating curve, it may be helpful in some cases to continue them on through the cooling cycle after the load has been removed. In this way the one set of observations may be used as a check on the other.

Conclusion

These notes have been prepared with the thought that they will serve their purpose if they show in a general way some of the conceptions that should be included in a broad review of the opportunities to effect system economies by the judicious application of emergency ratings.

List of Symbols

A, B, etc. = parameters
a, b, etc. = parameters
f = harmonic frequency, in cycles per hour
K_1, K_2, etc. = thermal capacity coefficients, in (watts)(hours)/(degrees centigrade)
P = maximum value of copper loss transient, in watts
p = instantaneous value of copper loss transient, in watts
R = ratio of maximum load to rating
r = instantaneous load
S_{12}, S_2, etc. = thermal dissipation coefficients, in (watts)/(degrees centigrade)
T_0 = threshold temperature, in degrees centigrade. It includes all constant components of the hot-spot temperature
t = time in hours
U = ratio of total installed emergency-load capacity to average yearly maximum demand
u = instantaneous ratio of emergency to normal load
x = dy/dt
y = thermal response (θ_1/P) to an impulse, in (degrees centigrade)/(watts)
Z = harmonic impedance of the thermal circuit
ϵ = base of Napierian logarithms
θ = hot-spot temperature (T_0 plus θ_1), in degrees centigrade
θ_1 = variable component of hot-spot temperature, in degrees centigrade
θ_a and θ_b = arbitrary components of θ_1
ω = $2\pi f$ radians per hour

Appendix A. Empirical Analysis of Temperature-Time Characteristic for a Rectangular Load Impulse

Given the test curve of temperature, such as shown in figure 7, which represents the temperature-time characteristic of a given assembly when subjected to a rectangular load impulse. The problem is to find the values of A, B, a, and b, which when substituted in the equation:

$$y = A(1 - \epsilon^{-at}) + B(1 - \epsilon^{-bt}) \qquad (13)$$

will make it fit the curve with reasonable fidelity for all values of t within the range of the observed data.

Select five points on the curve: one (t_1, y_1) which lies well up on the fast moving part of the curve; one (t_5, y_5) at $t = 0.5t_1$; and three others at about $t_2 = mt_1$, $t_3 = 2mt_1$, and $t_4 = 4mt_1$, in such a way that m is greater than 4, but $4mt_1$ includes no more than 80 per cent of the transient's apparent life. Graphically determine the slope x of the curve at each of the three latter points.

Now solve for b by considering the points (t_2, y_2), (t_3, y_3), and (t_4, y_4), which have been selected in such a way that they should be in the region where (at) is greater than 4, hence, for practical purposes,

$$y = A + B(1 - \epsilon^{-bt}) \qquad (13a)$$

and

$$\frac{dy}{dt} = Bb\epsilon^{-bt} = x \qquad (14)$$

From the observed slopes x_2, x_3 and x_4, then,

$$\frac{x_2}{x_3} = \epsilon^{b(t_3 - t_2)}, \quad \frac{x_2}{x_4} = \epsilon^{b(t_4 - t_2)}, \quad \frac{x_3}{x_4} = \epsilon^{b(t_4 - t_3)} \qquad (15)$$

From these three relationships it is possible to write directly the value of b which most nearly satisfies these observations.

$$b = \frac{1}{3}\left[\frac{\log_n(x_2/x_3)}{t_3 - t_2} + \frac{\log_n(x_2/x_4)}{t_4 - t_2} + \frac{\log_n(x_3/x_4)}{t_4 - t_3}\right] \qquad (16)$$

To solve for B substitute the value of b from equation 16, also (y_2), (y_3), and (y_4) respectively in equation 13a, as:

$$y_2 = A + B(1 - \epsilon^{-bt_2}), \; y_3 = A + B \times (1 - \epsilon^{-bt_3}), \; y_4 = A + B(1 - \epsilon^{-bt_4})$$

then

$$y_4 - y_2 = B_{24}(\epsilon^{-bt_2} - \epsilon^{-bt_4})$$
$$y_4 - y_3 = B_{34}(\epsilon^{-bt_3} - \epsilon^{-bt_4})$$
$$y_3 - y_2 = B_{23}(\epsilon^{-bt_2} - \epsilon^{-bt_3})$$

Hence

$$B = \frac{1}{3}\left(\frac{y_4 - y_2}{\epsilon^{-bt_2} - \epsilon^{-bt_4}} + \frac{y_4 - y_3}{\epsilon^{-bt_3} - \epsilon^{-bt_4}} + \frac{y_3 - y_2}{\epsilon^{-bt_2} - \epsilon^{-bt_3}}\right) \qquad (17)$$

To solve for A, substitute B, b, and the observed values of y_2, y_3, and y_4 in equation 13a, as:

$$A_2 = y_2 - B(1 - \epsilon^{-bt_2})$$

$$A_3 = y_3 - B(1 - \epsilon^{-bt_3})$$

$$A_4 = y_4 - B(1 - \epsilon^{-bt_4})$$

$$A = \frac{A_2 + A_3 + A_4}{3} = \frac{y_2 + y_3 + y_4}{3} - B + \frac{B}{3}(\epsilon^{-bt_2} + \epsilon^{-bt_3} + \epsilon^{-bt_4}) \quad (18)$$

To solve for a, consider the points t_0 and t_1 between the origin and the apparent "knee" of the curve. In this region it should be found that ϵ^{-bt} is very nearly equal to $(1 - bt)$. Otherwise select more suitable points nearer the origin, then substitute the new values of (t_1), (y_1), and $(\epsilon^{-bt_1} = 1 - bt_1)$ in equation 13 as follows:

$$y_1 = A(1 - \epsilon^{-at_1}) + Bbt_1$$

similarly,

$$y_0 = A(1 - \epsilon^{-at_0}) + Bbt_0$$

and from these,

$$a = \frac{1}{2}\left[\frac{1}{t_1}\log_n\left(\frac{A}{A + Bbt_1 - y_1}\right) + \frac{1}{t_0}\log_n\left(\frac{A}{A + Bbt_0 - y_0}\right)\right] \quad (19)$$

Equations 16, 17, 18, and 19 permit evaluating all the constants needed to make equation 13 represent the actual conditions about as well as the data from which they were developed. A sample calculation follows.

Sample Calculation of A, a, B, and b for Hottest of Eight Equally Loaded Cables in Duct in Earth

Given:

Point	t(Hours)	y	(dy/dt) = x
.....	0	0	
t_0	0.5	3.34	
t_1	1.0	5.60	
t_2	5.0	13.30	0.975
t_3	10.0	16.30	0.434
t_4	20.0	19.20	0.190

$$b = \frac{1}{3}\left[\frac{\log_n 2.25}{(t_2 - t_0) = 5} + \frac{\log_n 5.15}{(t_4 - t_0) = 15} + \frac{\log_n 2.29}{(t_4 - t_0) = 10}\right] = 0.118 \quad (16a)$$

$$B = \frac{1}{3}\left[\frac{19.2 - 13.3}{\epsilon^{-0.59} - \epsilon^{-2.95}} + \frac{19.2 - 16.3}{\epsilon^{-1.18} - \epsilon^{-2.95}} + \frac{16.3 - 13.3}{\epsilon^{-0.59} - \epsilon^{-1.18}}\right] = 12.90 \quad (17a)$$

$$A = \frac{1}{3}[13.3 + 16.3 + 19.2 - 38.7 + 12.90(\epsilon^{-0.59} + \epsilon^{-1.18} + \epsilon^{-2.95})] = 7.48 \quad (18a)$$

$$a = \frac{1}{2}\left[\frac{1}{1}\log_n\left(\frac{7.48}{7.48 + 1.52 - 5.60}\right) + 2.0\log_n\left(\frac{7.48}{7.48 + 0.76 - 3.34}\right)\right] = 0.819 \quad (19a)$$

$$y = 7.48(1 - \epsilon^{-0.819t}) + 12.90(1 - \epsilon^{-0.118t}) \quad (20)$$

A plot of equation 20, which is the upper curve drawn in figure 7, shows the manner in which it represents the observations from which it was derived.

Appendix B. Direct Analysis of the Two-Chunk Series Thermal Circuit with Constant Coefficients

The electric circuit which most nearly represents the relations between the usual thermal coefficients for the respective parts of the equivalent thermal circuits for transient load losses in transformers as well as cable installations, etc., is shown in figure 5 of this paper, in which (S_{12}) and (S_2) have the nature of conductances, (K_1) and (K_2) are thermal capacity coefficients, (p) has the nature of an electric current, and θ corresponds to the voltage rise required to cause "current" (p) to flow. Of the heat (pdt) flowing into part one, some $(K_1 d\theta_1)$ is absorbed by part one and the rest $(\theta_1 - \theta_2)S_{12}dt$ flows on into part two, hence:

$$pdt = (\theta_1 - \theta_2)S_{12}dt + K_1 d\theta_1 \quad (21)$$

and similarly, the heat entering part two $(\theta_1 - \theta_2)S_{12}dt$ is partly absorbed and partly dissipated through (S_2), or,

$$(\theta_1 - \theta_2)S_{12}dt = \theta_2 S_2 dt + K_2 d\theta_2 \quad (22)$$

By solving (21) and (22), first to eliminate (θ_2) and then (θ_1), the two following instantaneous relationships are obtained, one in terms of the hot-spot rise (θ_1) and the other in terms of (θ_2):

$$\frac{d^2\theta_1}{dt^2} + \left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right)\frac{d\theta_1}{dt} + \frac{S_{12}S\,\theta_1}{K_1K_2} = p\left(\frac{S_{12} + S_2}{K_1K_2}\right) \quad (23)$$

and

$$\frac{d^2\theta_2}{dt^2} + \left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right)\frac{d\theta_2}{dt} + \frac{S_{12}S_2\theta_2}{K_1K_2} = p\left(\frac{S_{12}}{K_1K_2}\right) \quad (24)$$

When the values of the S and K coefficients are constants and $p = P$ one solution for each of these linear equations takes the following form:

$$\theta = AP(1 - \epsilon^{-at}) + BP(1 - \epsilon^{-bt}) \quad (25)$$

In either case the values of a and b will be as follows:

$$a = \frac{1}{2}\left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right) + \sqrt{\frac{1}{4}\left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right)^2 - \frac{S_{12}S_2}{K_1K_2}} \quad (26)$$

$$b = \frac{1}{2}\left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right) - \sqrt{\frac{1}{4}\left(\frac{S_{12}}{K_1} + \frac{S_{12} + S_2}{K_2}\right)^2 - \frac{S_{12}S_2}{K_1K_2}} \quad (27)$$

while the values of A and B which make equation 25 represent θ_1, are

$$A = \left(\frac{1}{a - b}\right)\left[\frac{1}{K_1} - b\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right] \quad (28)$$

$$B = -\left(\frac{1}{a - b}\right)\left[\frac{1}{K_1} - a\left(\frac{1}{S_{12}} + \frac{1}{S_2}\right)\right] \quad (29)$$

Conversely, if equation 25 accurately represents test observations of the hot-spot temperature (θ_1), the effective values of K_1 K_2, S_{12}, and S_2 become:

$$K_1 = \frac{1}{aA + bB} \quad (8)$$

$$S_{12} = K_1(a + b) - K_1^2 ab(A + B) \quad (9)$$

$$S_2 = \frac{S_{12}}{S_{12}(A + B) - 1} \quad (10)$$

and

$$K_2 = \frac{S_{12}S_2}{abK_1} \quad (11)$$

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Discussion

R. J. Woodrow (Philadelphia Electric Company, Philadelphia, Pa.): In his analysis Mr. Kidder has shown that the approximate thermal circuit given by figure 5 of his paper can be replaced by and used interchangeably with the empirical circuit of figure 6 in order to analyze the temperature rise θ_1, and has given equations in appendix B by which the constants of either circuit can be calculated from those of the other. This is particularly valuable in investigating the thermal characteristics of a number of types of electrical equipment such as transformers, regulators, oil circuit breakers, and cables, whose thermal heating circuits are for all practical purposes composed of two parts as shown in figure 5.

In order to determine rapidly and simply the constants a, b, A, and B of the empirical

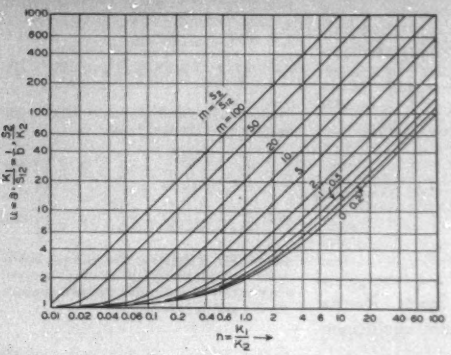


Figure 1

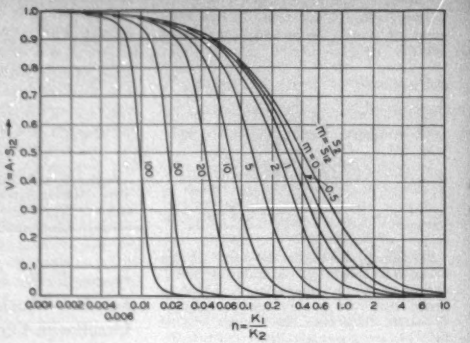


Figure 2

circuit of figure 6 of Mr. Kidder's paper from the constants S_{12}, S_2, K_1, and K_2 of the circuit of figure 5, three sets of curves have been drawn and are shown in figures 1, 2, and 3 of this discussion. By entering these curves with $n = K_1/K_2$ and $m = S_2/S_{12}$, A and B can be determined directly in per unit of the corresponding thermal resistances $1/S_{12}$, and $1/S_2$ of figure 5, and a and b in per unit of the corresponding reciprocal time constants S_{12}/K_1 and S_2/K_2. The relations which apply when using the curves are as follows:

Enter curves with $n = \dfrac{K_1}{K_2}$ and $m = \dfrac{S_2}{S_{12}}$

Read values of U, V, and W.

Then

$$a = U \cdot \frac{S_{12}}{K_1} \qquad b = \frac{1}{U} \cdot \frac{S_2}{K_2}$$

$$A = V \cdot \frac{1}{S_{12}} \qquad B = W \cdot \frac{1}{S_2}$$

As stated by Mr. Kidder the temperature differences θ_a and θ_b of the empirical circuit of figure 6 have no real significance and actually do not exist in the equipment. There are some cases, however, in which these temperature differences are so nearly the same as those that actually do exist across parts 1 and 2 of the circuit of figure 5 that, practically, they may be assumed to be the same. From the curves it may be seen that when $n = K_1/K_2$ is less than 1/50, and $m = S_2/S_{12}$ is less than 1/1, the constants of the empirical circuit and those of the actual circuit do not in any case differ by more than five per cent. Thus in an oil-filled transformer, for example, where the above limiting values of m and n are somewhat representative, there is not much error in considering the thermal circuits as if the constants of figure 5 were identical to those for figure 6 (that is, $U = V = W = 1.0$).

Equation 4 of Mr. Kidder's paper can be rewritten slightly as follows to give the temperature θ_1:

$$\theta_1 = P[A(1 - \epsilon^{-at}) + B(1 - \epsilon^{-bt})]$$

in which there are two exponential terms with different time constants. It should be pointed out that not only does the solution for θ_1 have two exponential terms, but θ_2, the temperature rise of part 2, and $\theta_1 - \theta_2$, the temperature difference across part 1 of figure 6, also have two exponential terms with the same time constants in their solutions. Thus:

$$\theta_2 = \frac{P}{S_2}\left[1 - \frac{1}{a-b}\left\{a\epsilon^{-bt} - b\epsilon^{-at}\right\}\right]$$

$$\theta_1 - \theta_2 = \frac{P}{S_{12}}\left[1 - \frac{1}{a-b}\left\{\left(\frac{S_{12}}{K_1} - b\right)\epsilon^{-at} + \left(a - \frac{S_{12}}{K_1}\right)\epsilon^{-bt}\right\}\right]$$

Again taking transformer heating as an example, this means that the top oil temperature rise (θ_2) has both a slow-moving and a fast-moving term in its response to a steadily applied load, the fast-moving term being opposite in sign to that of the slow-moving term and thus causing θ_2 to rise less rapidly for a short time after the load is applied. Likewise in the temperature rise ($\theta_1 - \theta_2$) of winding above top oil temperature there are both fast-moving and slow-moving exponential terms. However as previously pointed out, with n approximately 1/50 and m approximately 1/1, the error is not large in considering the top oil temperature as having a single slow-moving term in its response, and the winding rise above top oil as having a single fast-moving term in its response.

Although it is approximately correct to assume that the heating of an assembly having a thermal circuit such as given by figure 5 of Mr. Kidder's paper is practically the same as given in figure 6 with no change in constants if n is less than 1/50 and m less than 1/1, when these ratios increase the error rapidly becomes larger. For example if $K_1 = K_2$ and $S_{12} = S_2$ (that is, $m = n = 1.0$), then the following values result:

$$a = 2.62 \cdot \frac{S_{12}}{K_1} \qquad b = 0.38 \cdot \frac{S_2}{K_2}$$

$$A = 0.11 \cdot \frac{1}{S_{12}} \qquad B = 1.89 \cdot \frac{1}{S_2}$$

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): I wish to comment on the statement made in the last paragraph preceding the conclusion to the effect that in oil-filled transformers the hot-spot temperature at any time should be about equal to the average winding temperature plus the difference in temperature between the top oil and the oil opposite the midpoint of the winding.

When first reading this rule, I felt that it would not be a safe rule to follow under heavy overload conditions. Further investigation, however, showed that in general it gives approximately correct results up to 150 per cent load. Nevertheless, I wish to qualify the statement about its being a safe rule to follow under all conditions. While

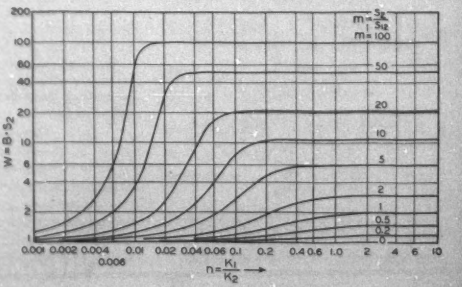


Figure 3

there is a certain relationship between the hot-spot temperature (and by hot spot I mean the difference between the maximum and the average winding temperatures) and the difference between the top oil and average oil temperature, factors other than the vertical temperature gradient affect the hot-spot temperature. One of these factors is current density in the copper coupled with the type of coil. One design may have a low current density, while another design has a high current density, yet both may have the same vertical oil gradient. The hot spots may be quite different in the two designs.

Another factor which the rule does not take into consideration is eddy-current losses which may not be uniformly distributed throughout the windings. Hot-spot temperatures will in general range from four or five degrees to ten degrees at normal load, the average probably being about seven degrees.

To see how the rule worked I took a typical case assuming that at normal load both the vertical oil gradient and the hot spot was seven degrees and found that at 125 per cent the rule was in error by approximately one degree (too low) and at 150 per cent the rule was in error approximately two degrees. This is close enough for all practical purposes.

On the other hand, if the hot spot is ten degrees at normal load and if the oil gradient is seven degrees, the rule, when used for 125 per cent load, would be in error by approximately five degrees. For 150 per cent load the error would be approximately eight degrees.

Since the rule covers only the vertical oil gradient factor that affects the hot-spot temperature, some care should be used in applying it in the field. It is easy to use if the user knows where the midpoint of the winding is by placing two thermometers on the outside of the tank—one at the top and one opposite the midpoint of the windings.

E. R. Thomas (Consolidated Edison Company of New York, Inc., New York): Mr. Kidder is to be congratulated in assembling together the factors to be considered in designing a transmission and distribution system. In obtaining equations 1 and 2, I assume that the derivation is based only upon a first contingency. As the number of units increases numerically to values greater than seven, as for example in the number of feeders being considered into an a-c network area, operating experience has shown that it is not uncommon to have a second contingency. I would like to ask the author whether, in his opinion, consideration should be given to second contingencies as affecting the average ratio of emergency load rating to normal rating when five or more units are being treated as a design combination.

F. H. Buller (General Electric Company, Schenectady, N. Y.): Mr. Kidder's primary purpose in presenting this paper appears to be the development of a method whereby the efficiency of utilization of existing plant may be increased. It is evident that considerable savings will result if it is feasible to carry increased loads on existing plant without overloading the aforesaid plant, and Mr. Kidder proposes to do this by what amounts to a material reduction in the amount of spare capacity available for use during emergencies.

This of course may result in the overloading of the plant when such emergencies actually arise; and Mr. Kidder has attempted to discover just about how much such overloads are likely to damage the existing cable.

He has shown in his paper that an overload of approximately 25 per cent, as compared with the maximum the cable should carry according to the AIEE temperature rules, will produce a very material increase in cable failures. Just what proportion of the $4^1/_2$ times figures which he gives can be directly attributed to the overload, cannot be established very clearly without knowing the peak loads which the cable was carrying in the ten years prior to the application of the long-time overload; but it must be a very considerable proportion of the figure in question.

Furthermore, Mr. Kidder points out that the failures which have resulted from the overload to date have almost all been sheath failures, caused by abrasion, or by bending of the cable in the manhole, particularly in the neighborhood of the duct mouth. We would expect his failure rate to increase materially with time rather than to decrease for two reasons. First, the lead sheath is materially weakened by high temperatures; and while three years of operation would probably weed out most of the weak spots in the lead sheath, and also the spots which are materially overstressed due to repeated bending as compared with the rest of the cable, it is possible that other weak spots have been developed in the sheath of the remaining cable due to the high temperatures, over and above those which have been found already; and these weak spots might never have existed had the cable been operated at a more normal temperature. Moreover, the bends in the manholes at the duct mouths are still in operation and will probably contribute just as much to the cable failure rate as they ever did, if the high-temperature load cycles are maintained.

Second, the wide range of temperature which is encountered on these cycles will unquestionably cause considerable sheath stretching and compound migration even where no sheath failure actually occurred. This means that void formation and ionization will be much more severe under these wide temperature cycles than would be the case if the AIEE limitations were respected. Now void formation and ionization usually tend to work quite gradually in producing cable failures, unless they are extremely severe from the beginning; and the fact that few failures have occurred as yet due to deterioration of the insulation does not mean that a large number of failures may not occur in the future due to these causes.

With regard to the mathematical derivation given in appendix *B* and covering a direct analysis of the two-chunk series thermal circuits, this analysis should probably work out pretty well for low-voltage cables and for cables of intermediate voltage.

Mr. Kidder points out that for overhead lines without insulation that one exponential term is sufficient. The reason for this is self-evident. The thermal resistance of the copper in such a circuit is exceedingly low, and there is no thermal resistance of the insulation; consequently all the thermal resistance is concentrated at the surface of the conductor, and is therefore actually a concentrated constant. The thermal capacity of the copper is the only thermal capacity involved in the heat dissipation of a system of this sort; and this is also for all practical purposes a concentrated constant. For two concentrated constants of this type a single exponential term is sufficient to represent the performance of the system mathematically, just as a single exponential term is sufficient in an electrical circuit containing concentrated resistance and capacitance.

If the insulation of the cable possesses appreciable thermal resistance and capacitance, however, we have a condition more nearly analogous to an electrical transmission line with distributed resistance and capacitance than to an electric circuit with concentrated constants. If the insulation is thin, it is possible to get reasonably accurate results by the use of a single exponential term to represent the entire cable, just as it is possible to represent a short transmission line with distributed constants by an equivalent circuit with concentrated constants. When the line gets long, or when the insulation gets thick, due allowance must be made for the fact that the constants are actually distributed. Various people, including the present writer, Mr. Church of Boston, and Mr. Miller of Chicago, have developed methods of doing this, but they all lead to a series of the general form of equation 3 in Mr. Kidder's paper and are quite complicated to apply in practice.

Incidentally, it should be noted that while successive terms of this series may converge quite rapidly toward zero the rate of change in each term does not converge nearly so rapidly. The use of distributed constants is therefore more important in problems involving the rate of change in temperature than in problems involving only the temperature itself. Experience indicates that these additional terms contribute materially to the rate of change in temperature for a period ranging from 5 minutes to 30 minutes after the application or dropping of load; this may affect the choice of the first point on the curve when analyzing time-temperature characteristics empirically in accordance with the method outlined in appendix *A* of Mr. Kidder's paper.

Mr. Kidder's second exponential term represents the cooling of the duct bank rather than that of the cable itself. Empirical information of this sort is extremely valuable, since it is very difficult to establish accurate mathematical equations for the cooling of a duct bank, and even if these equations were established, they would be of little value without the corresponding constants which can only be obtained empirically

One point on page 9 of Mr. Kidder's paper deserves a little further consideration. The writer is of the opinion that the threshold temperature T_0 should correspond to the sum of the ambient temperature, a steady-state rise caused by no-load losses, and the copper-temperature rise corresponding to the actual cable temperature at the time of the application of the overload rather than to the average daily copper loss. For the sake of safety, it would probably be advisable to assume that the overload occurs at or

near the peak of the daily load cycle, since there is absolutely no guarantee that it shall not occur there, and since if the overload persists for as long as 24 hours it is absolutely certain to hit the peak of the daily load cycle at some time or other. Just how close it should be assumed to the peak is a matter for individual judgment; but certainly it would appear that it should be assumed to hit the cable at some temperature higher than that caused by the average daily losses.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): The author's approach to the problem of emergency ratings is interesting and should help in working out individual situations. However, to deduce generalities by means of probability laws requires many basic assumptions, some of which are not as yet well established. A more definite idea on the matter will come from more experience than just the three years of operation of 22 miles of cable at high temperatures cited by the author.

As pointed out in my paper ("Load Ratings of Cable," AIEE TRANSACTIONS, volume 58, 1939, pages 535-56) cable movement is not directly proportional to the square of the load, as was assumed by the author. Also, the rate of sheath troubles due to repeated daily bending in the manhole increases more rapidly than the first power of the magnitude of the cable movement. Furthermore, consideration of troubles should not only include the very important matter of sheath cracks but should also include the effect of high temperature on the insulation. This is especially important for some of the old high-voltage cables which have high dielectric losses. In some of the newer cables with thick insulation and oil fed at the joints, the effects of oil movement and sheath expansion must also be considered.

Any problem of loading including emergency loading must consider the economics for the system as a whole and the probable shortening of the life of the cable by the use of the higher temperatures.

A. H. Kidder: As should perhaps be expected for a paper of this sort, the discussion has been the more helpful because space did not permit a complete summary of the thoughts behind each of its observations. The points raised will be reviewed in the order in which they were brought out in the discussion.

V. M. Montsinger's comments on the author's suggestion for determining the approximate hot-spot temperature in a test on an oil-filled transformer, give a valuable indication of the probable magnitude of error. One to eight degrees centigrade at 150 per cent load is usually well within the over-all limits of error faced in making the practical compromises between accuracy and convenience that assume important proportions in most electric distribution problems. The author's method assumes that the vertical gradient in the winding is that of the oil alone. The method will, therefore, be in error to the extent that current density and eddy currents distort the vertical temperature gradient. The author's only claim for his method is that it provides a convenient means for approximate recognition, during a test at constant load, of the oil temperature gradient as an important component of the instantaneous hot-spot rise above average winding temperature.

E. R. Thomas's suggestion of the need for considering second contingencies should not be overlooked in dealing with large numbers of units n in equations 1 and 2. Their probable frequency of occurrence and their effect upon the curves in figure 3 of the paper may be evaluated approximately by the method outlined for first contingencies.

The severity of second-contingency loading naturally decreases to some extent when the number of units increases in a given design combination, while the likelihood of facing a second contingency increases with the number of units in the group.

F. H. Buller's thoughts on the possible causes of cable failures at high temperatures are quite similar to those which have occurred to the author from time to time. The instance of daily repeated high-temperature operation for 13.2-kv cables probably stands by itself in that it is much more severe than would be justified in any ordinary situation. Should the cable have been destroyed already, the station economies have been adequate to finance their replacement with new and larger cable. In the meantime, the experience being accumulated from such a full scale "accelerated life test" should in time answer approximately some of the interesting questions Mr. Buller has raised. The point that the author apparently failed to drive home, however, is that the cables cited in this instance have already done on at least 600 occasions what they would not be expected to do once in 100 years, if they were in the service represented by figure 3 of the paper which assumes strict observance of the AIEE limitations for all regular daily operations.

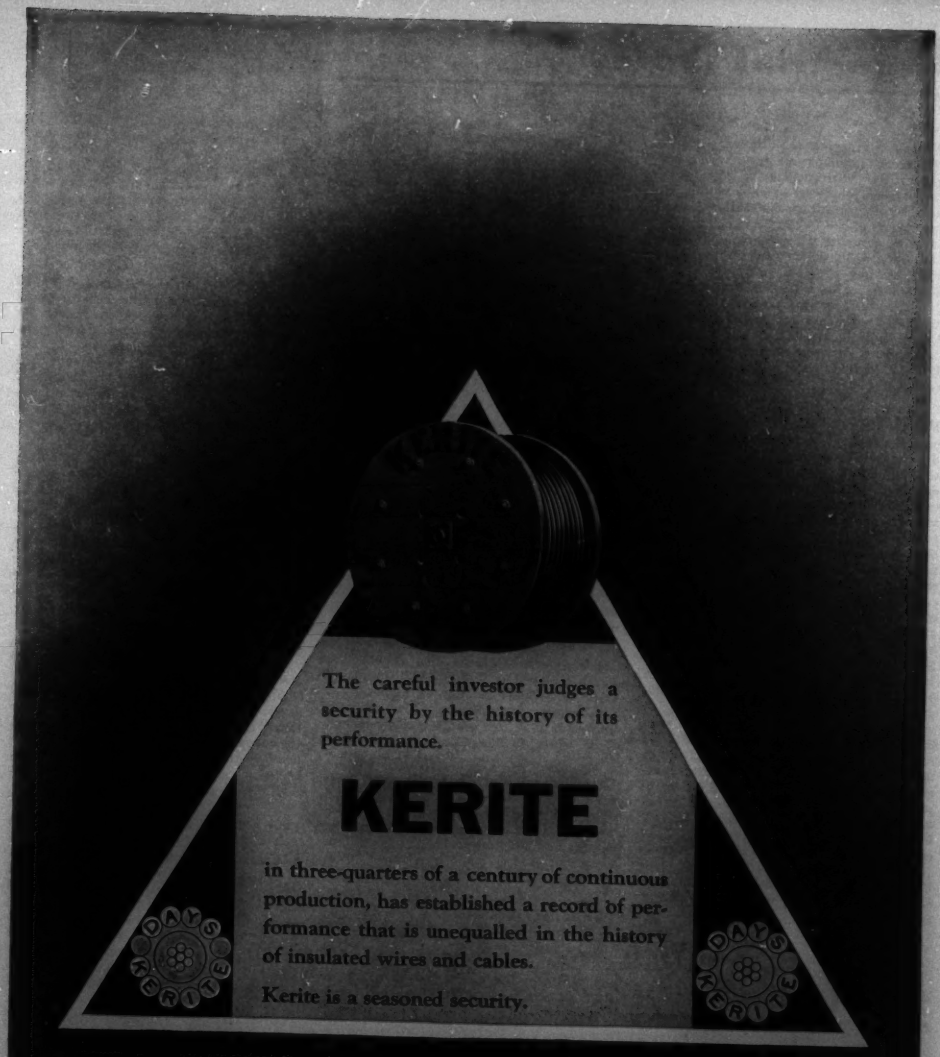
Mr. Buller's suggestion of the need for care in selecting the first point on the curve, when analyzing temperature-time characteristics empirically in accordance with the method of appendix *A*, raises an interesting point. Practical tabular calculations of the temperature transients which accompany normal or emergency load cycles do not require close agreement between the approximate and the true responses to load impulses of less than one-half hour duration on any assembly, because any possible effect of the circuit transient phenomena which are responsible for inaccuracies in this region will disappear within so very short a time in comparison to the duration of the load cycle under consideration. Emergencies which expire within one hour are almost always easiest and best treated as if the accompanying change in load losses were a rectangular impulse, for which the correct value of the response is directly proportional to the readings available on the true temperature-time characteristic.

The threshold temperature T_0 to which Mr. Buller refers was taken to be that level above or below which all temperature changes move because of deviations p from average copper losses in the cable in question. For safety the author prefers to start the tabular calculation of cable temperature at the time during the day when the normal values of p are changing from negative to positive quantities and to assume arbitrarily that the initial value of Θ_1 is zero, instead of the slightly negative value it would have at that time. To determine the approximate copper temperature at any other time it is then necessary only to use in the tabular calculation, the successive values of p which represent the anticipated time sequence of the instantaneous normal and emergency loads. In this way the calculation automatically will include proper recognition of the temperature attained by the time the emergency load is applied, and without need for redefining threshold temperature.

The maximum temperature is usually reached well toward the close of the day's normal heavy-load period and often within an hour or two after the peak. The highest emergency temperature, therefore, accompanies the state of emergency which begins at such a time that normal loads cannot be restored until just after the close of the peak load period. Often the time required for restoration of normal conditions is short enough so the emergency values of p need not be introduced in the tabular calculations prior to the time when Θ_1 may safely be assumed to be zero, as described above. The calculation may also begin at the same point on the load curve when it is desired to initiate emergency loading still earlier in the day, but should follow the normal values of p in reverse time sequence until the instant the emergency values of p will be applied and then proceed as usual. There is always the alternative of calculating one complete temperature curve for a normal day's load cycle, as a means for determining the time of maximum temperature and the conditions at the time it is then decided to start the emergency temperature calculations.

R. J. Woodrow's discussion contributes material which should be very helpful to those investigating the thermal characteristics of a number of different types of electrical equipment.

The data assembled by Mr. Halperin unmistakably support his comments on cable movement and its effect upon formation of sheath cracks. Each other possible cause of cable failure probably likewise has its own special characteristic, so that the over-all effect cannot be calculated deductively without first establishing all of these relationships. There is much to be gained from actively accumulating the facts needed to evaluate these relationships. In the meantime, however, cases of high-temperature operation such as cited by the author should give a fair, though empirical, indication of the approximate manner in which the over-all failure rate will follow moderate changes in the average-day loading of similar cables. Whether three years, or about 600 load cycles, of high-temperature experience can give a practical answer to the effect of temperatures upon the over-all failure rate, would appear to depend appreciably upon how many such high-temperature load cycles will be imposed upon the cable in question. It is the author's opinion that the AIEE limits are none too conservative for normal operating conditions, also that the possibility of infrequent temperature excesses during emergency load periods should give no cause for alarm.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Industrial Notes

Expansion Programs for Utilities.—Some of the recent announcements covering new generating facilities contracted for by power companies include a 50,000-kw unit and auxiliary equipment for the Marion generating station of the Public Service Electric & Gas Co., at a cost of approximately $7,500,000; and a 35,000-kw unit and accessory apparatus for the Consumers Power Co., $9,000,000. Also, a 40,000-kw unit for the Narragansett Electric Co., $4,000,000; and a 50,000-kw program for the Public Service Co. of Indiana, $6,400,000. A 25,000-kw unit and auxiliary equipment for the Florida Power & Light Co. is also planned at a total cost of $3,000,000.

Manufacturers' Sales Rise.—Orders received by the General Electric Company during the third quarter of 1939 amounted to $79,510,000 compared with $60,533,000 during the same quarter last year, an increase of 31 per cent. For the first nine months this year orders received amounted to $248,582,000, an increase of 32 per cent over the $188,757,000 received during the same period a year ago. Sales billed during the first three quarters totaled $217,900,154 compared with $192,501,173 during the corresponding period of 1938, an increase of 13 per cent. . . . . Orders booked by the Westinghouse Electric & Mfg. Company for the first nine months of 1939 were $153,976,777 as compared with $113,170,228 for the same period in 1938, an increase of 36 per cent. For the twelve months ended September 30, orders were $190,469,325, compared with $151,509,531 for the same period in 1938, an increase of 26 per cent. Sales billed for the first three-quarters of 1939 were $129,602,676 compared with $119,550,418 for the same period in 1938, an increase of 8 per cent. Billings for the twelve months were $168,025,474 compared with $171,038,728 for the same 1938 period, a decrease of 2 per cent. Unfilled orders at September 30, 1939 were $58,337,790 compared with $43,817,402 at September 30, 1938.

Trade Literature

Graphic Wattmeters.—Bulletin 839, 12 pp. Describes five types of graphic wattmeters available in portable, switchboard and wall types. The Esterline-Angus Co., Indianapolis, Ind.

Capacitors.—Catalog 164, 36 pp. Describes industrial capacitors for motor starting and other a-c applications. Includes data on physical and electrical characteristics, and other information required for economical and satisfactory applications. Cornell-Dubilier Electric Corp., South Plainfield, N. J.

Air Cooled Transformers.—Bulletin, 4 pp. Describes complete new line of low-priced, air-cooled transformers ranging from 1 va to 10 kva. Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City.

Parkway Cable.—Bulletin GEA-3244, 4 pp. Describes tellurium rubber-sheathed, non-metallic parkway cable, resistant to moisture and soil acids and alkalies. General Electric Co., Schenectady, N. Y.

Motors.—Bulletin 938A, 12 pp. Describes repulsion start, induction brush lifting, single phase motors. Characteristics of these type motors and applications are outlined. Century Electric Co., St. Louis, Mo.

Bearings Size Finder.—Made in the form of a slide rule, this unique device enables the user to quickly select appropriate sleeve bearings among over 800 stock sizes. Johnson Bronze Co., New Castle, Pa.

Molten-Welding Copper to Steel.—Bulletin 8 pp. Illustrated in color. Describes the unique process of molten-welding copper to steel in the manufacture of "Copperweld" wire and strand and ground rods. Copperweld Steel Co., Glassport, Pa.

Transformers.—Bulletin 109, 8 pp. "A Plant Equipped for Building Transformers." Entirely devoted to showing facilities for transformer manufacture. The bulletin illustrates also the offices and personnel. R. E. Uptegraff Mfg. Co., Scottdale, Pa.

Chain Drives.—Cat. V-135, 64 pp. Gives complete information for the selection and design of silent chain drives and includes engineering data, dimensions, horsepower ratings and illustrations of typical drives in various industries. The Whitney Chain & Mfg. Co., Hartford, Conn.

Distribution Cutout.—Bulletin 65. Describes type "ET-2," non-drop-out distribution cutouts; capacities 5, 7.5, 12.5 and 15 kv; available in two ratings, —1 to 50 amperes and 50 to 100 amperes. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

Motor Control.—Booklet 88, 24 pp., "Custom-Built Automatic Motor Control." Describes and illustrates numerous examples of control apparatus designed and built for various types of motors used for special purposes. The Electric Controller & Mfg. Co., Cleveland, O.

Condensers.—Catalog, 28 pp. Describes a complete range of condensers of all types as well as essential resistors and test instruments. New items covered include the L-C checker for testing condensers and inductances, and the motor-starting capacitor selector and emergency unit kit. Complete specifications are included; the various condenser types are classified and indexed enabling the quick location of any type desired. Aerovox Corporation, New Bedford, Mass.

Rotary Switches.—Catalog 9, 12 pp. Describes type R-2 instrument and control switches. Such switches are flexible in design and completely cover the field of apparatus control, whether the requirement is standard or special, on circuits up to 600 volts. Includes complete listings, with prices, technical data, diagrams of connections. Roller-Smith Co., Bethlehem, Pa.

Mill Motor Protection.—Bulletin 3910, 12 pp. A reprint of a comprehensive paper entitled "Protection of Branch Circuits for Steel Mill Auxiliary Motors," which describes in detail the various types of control and air circuit breaker equipment used and the factors entering into the selection of adequate apparatus best suited for the purpose. I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Pa.

Welding Practise.—Bulletin, 20 pp., "101 Welding Ideas for Low Cost Maintenance." Illustrates and describes a wide variety of money-saving repair, fabrication and structural applications of arc welding. Outlines, by case studies of 101 actual maintenance jobs, just how general repair work and fabrications are accomplished by the arc welding process. The Lincoln Electric Co., Cleveland, O.

Insulators.—Catalog 6, 128 pp. Describes vacuum process high-voltage insulators and accessory clamps and fittings for transmission, distribution, substation and special applications. Arranged to simplify selection of appropriate insulators and hardware, the volume constitutes an unusually comprehensive treatment, covering production, complete specifications and applications. Lapp Insulator Co., Inc., LeRoy, N. Y.

Electrical Steel Sheets.—Technical Bulletin 1, 116 pp. Contains major characteristic curves of the guaranteed grades of USS electrical steel sheets with descriptions and explanations of the use of the grades and curves. These include core loss, magnetization, core loss and volt-ampere, hysteresis loops, and frequency vs core loss. For the first time separate curves are presented for the three commonly used gages showing the entire magnetization characteristics of USS electrical steel sheets over a magnetizing range of 1,000,000 to 1. Included are various data, tables and curves of value in connection with electrical equipment design and the selection of the proper grade and gage of steel to use. Also shown are magnetization curves of other USS products in sheet and plate form used in electrical machines. All curves and data presented were obtained from measurements made in the Carnegie-Illinois Electrical Sheet Laboratories and represent the latest technical information available. The bulletin is available to designers or manufacturers of electrical equipment and engineering schools for use in connection with their technical courses. Sheet Division, Carnegie-Illinois Steel Corp., Pittsburgh, Pa.

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Broad flexibility plus accuracy for routine current testing. Ranges . . . 10/20/50/100 Amperes self contained Primary; maximum of 800 amperes with Inserted Primary.

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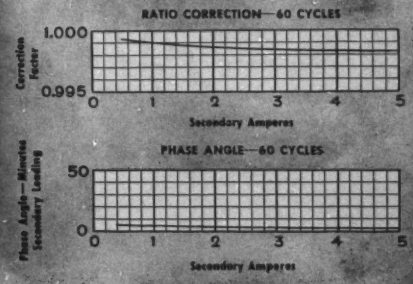

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Extreme accuracy plus flexibility for certification work. Ranges: 10/20/50/100 Amperes at binding posts; and 200/300/400/600/1200 Amperes with Inserted Primary.

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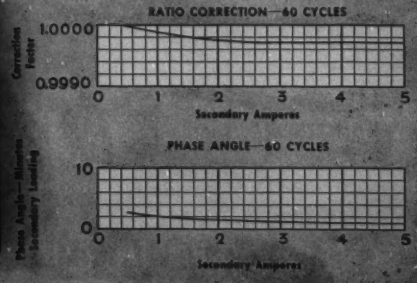

Complete details on these and other WESTON portable Current and Potential Transformers for laboratory and commercial testing are available in bulletin form. Send for your copy.

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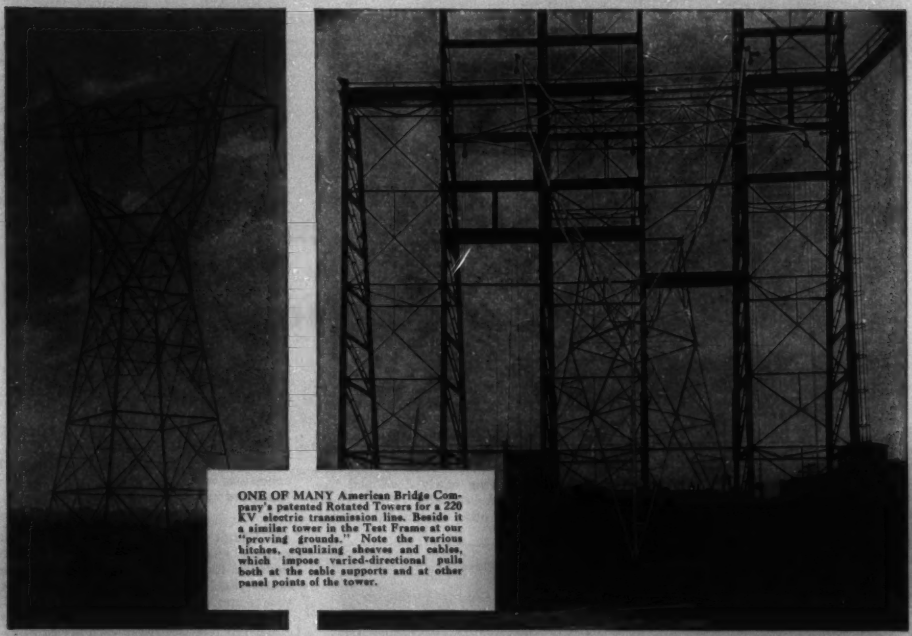
I·T·E CIRCUIT BREAKER CO., PHILADELPHIA, PA.

AMERICAN BRIDGE "PROVING GROUNDS" put Line-Towers through the "ACID TEST"



ONE OF MANY American Bridge Company's patented Rotated Towers for a 220 KV electric transmission line. Beside it a similar tower in the Test Frame at our "proving grounds." Note the various hitches, equalizing sheaves and cables, which impose varied-directional pulls both at the cable supports and at other panel points of the tower.

NOT only our own, but other leading engineers verify design calculations by turning to our "Proving Grounds" for thorough tests on full size line-towers. For our Shiffler Plant facilities include the largest and most modern Test Frame in the country—if not in the world—for testing even the tallest line-towers in present day use. Mechanically equipped to exert vertical and horizontal pulls, singly or in combination and at any point of the tower, this Frame in effect duplicates field loading conditions that conform to any specified design criteria, such as:

1. **Vertical loadings due to weight of cables and fittings—ice-coated.**
2. **Horizontal forces, transverse to the line, that typify wind loads and forces due to angular change in alignment.**
3. **Unsymmetrical horizontal pulls, parallel to the line, exemplifying torsional strains due to broken wires.**
4. **Test to destruction under the combined loading conditions as provided in specifications by the customer.**
5. **Tests based on either a rigid foundation condition or the usual earth footing anchorage according to designed requirements.**

Thus, not only do we design, fabricate, galvanize and erect all types of transmission towers, but also we give them the "acid test" of actual working conditions at our "proving grounds."

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UNITED STATES STEEL

New Products

Electrical Contacts.—Possessing the high conductivity of pure silver as well as its low, constant resistance, electrical contacts are now being marketed to manufacturers of electrical equipment under the trade name of "Gibsiloy" by the Gibson Electric Co., 567 Boulevard of the Allies, Pittsburgh, Pa. Because of its ductility, Gibsiloy, a powdered metal composition, may be formed into a wider variety of shapes than similar materials which, owing to their brittleness, must be cast to form. Moreover, Gibsiloy may be punched, machined, drilled, tapped and otherwise worked as easily as ordinary alloys.

Some of the many shapes available, both of solid Gibsiloy and with it attached to base metal backings, are shown in the accompanying illustration. Such contacts are much harder than those made of pure silver and resist wear to a far greater degree. Hardnesses range from that of pure silver to 200 Brinell B scale Shore Scleroscope for some grades of silver-nickel-tungsten. The most common forms of Gibsiloy are silver-nickel, silver-nickel-cadmium, silver-nickel-tungsten, silver-nickel-molybdenum, silver-tungsten, and silver molybdenum. Each form is produced in different grades possessing varying physical properties.

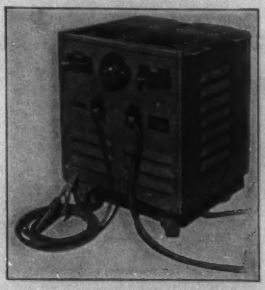
Auxiliary Circuit Breaker.—A small, fully electro-magnetic, non-thermal auxiliary circuit breaker, in explosion-proof housing, for a-c 110- and 220-volts, manufactured by the Heinemann Circuit Breaker Co., Trenton, N. J., is available in ratings up to 1 hp and

25 amperes, for use in all hazardous locations where fumes, acids, gases and dust are prevalent in the atmosphere. The breaker has magnetic instantaneous trip on short circuits and magnetic time delay on harmless overloads.

Flexible Copper Braids.—The flexible copper braid jumpers developed by the Burndy Engineering Co., Inc., 459 E. 133d St., New York City, are suitable for carrying instantaneous currents up to 30,000 amperes

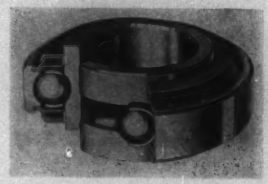
such as may be used in heavy welding equipment. The inner ends of the copper ferrules are belled to prevent excessive stress concentration in the strands as they leave the ferrules. Curved or straight braid assemblies with the ends compressed into a solid mass in the ferrules have been made for any ampere capacity desired. A wide variety of connectors of other types have also been introduced by this company.

Electronic Arc Welder.—A novel design of low-current, electronic arc welder for precision work, called the "WELD-O-TRON" unit, and introduced by the Allis-Chalmers Manufacturing Co., Milwaukee, Wis., can be used to weld with currents as low as 5 amperes, employing newly developed $^1/_{32}$-inch and $^3/_{64}$-inch electrodes. Steels, stainless steels, and other metals lighter than



approximately 18 gauge, can readily be welded. The new equipment is said to be applicable to many types of work previously considered too small or too light in construction for anything except riveting, spot welding, brazing or even soldering. Sheets as thick as 0.010", or approximately 32 gauge, can be handled without any difficulty. The heart of the portable WELD-O-TRON electronic arc welder is a multiple tube, polyphase, mercury vapor rectifier unit. It makes use of the newest type of rectifier tubes, specially developed for this equipment. The unit combines light weight, long life, and absence of rotating parts with the advantages of both a-c and d-c arc welding.

Mechanical Bearing Seal.—A new bearing development by The Fafnir Bearing Company, New Britain, Conn., termed the "Mechani-Seal," now commercially available in various combinations, provides unusually high sealing efficiency without conventional felt seal or other contact material which would cause friction and heat. It insures the retention of the lubricant and eliminates the possibility of entrance of foreign matter into the bearing. Two steel plate shields, widely separated to form a trap, serve as the innermost members, both attached to the outer bearing ring. Another steel plate, pressed on the bearing inner ring, acts as a slinger when this inner ring is rotating. Definite, though extremely close clearances exist between the individual members so that nothing is added to the total bearing friction. The outer members, in addition, are given a corrosion and rust-proof treatment. According to the manufacturer, during the two years of testing of



the Mechani-Seal, more than a hundred bearings equipped with this seal were successfully tested under various speeds and conditions more severe than would be encountered in actual use.

Air Circuit Breaker.—A new air circuit breaker, recently announced by the Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa., is approximately one-half the size of previous devices of the same rating. Among the most important improvements is the "De-ion" arc chamber, a device which is simple in construction, operated on either alternating or direct current, has long life, and under normal operating conditions requires no maintenance. It operates on any current within the range of established interrupting ratings; arcing current is limited to one-half cycle, which minimizes the noise and flash accompanying the interruption of a short circuit. The circuit breaker itself is stronger than previous air breakers. No carbon is used in the contacts; and the protective contact supports have been strengthened. Heavy current through the flexible conductors to contact supports causes a magnetic reaction that increases contact pressure and gives increased protection to the main contacts. Five sizes are available, covering a range of operating currents from 15 to 6,000 amperes at 600 volts on a-c service—15 to 10,000 amperes direct current—and have interrupting capacities of from 40,000 to 80,000 amperes.

For new list of available pamphlet copies of AIEE papers, see page 2, advertising section.

NEW OSCILLATOR

with Exceptionally Low Distortion

INCORPORATING a new inverse feedback circuit of very high selectivity, the G-R Type 608-A Oscillator supplies good output at twenty-seven discrete audio frequencies, remarkably low in harmonic distortion.

This oscillator makes possible bridge measurements at the lowest audio frequencies with considerably higher accuracy than has been possible heretofore. It provides a very rapid method for obtaining a large number of audio frequencies.

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- **WIDE FREQUENCY RANGE**—20 to 15,000 cycles in 27 steps selected immediately by two push-button switches; any additional frequencies within this range can be obtained by connecting three resistors to appropriate terminals
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- **GOOD STABILITY**—at room temperatures, frequency will not drift more than 1% over a period of several hours
- **THREE OUTPUT IMPEDANCES**—500-ohm balanced to ground; 500-ohm unbalanced; 5,000-ohm unbalanced . . . selected by push-button switches
- **LOW HUM LEVEL**—less than 0.05% or 0.1 millivolt
- **EXCELLENT WAVEFORM**—adjustable by means of harmonic control on panel; at maximum power output harmonics are 5% of output voltage; when output voltage is reduced by 10% total harmonic contact is reduced to 0.02%; harmonics can be reduced to less than 0.1% for all output frequencies with the 5,000-ohm output circuit
- **MAXIMUM OUTPUT POWER**—with the 5,000-ohm circuit, approximately 0.5 watt; with the 500-ohm circuits, 80 milliwatts

Type 608-A Oscillator **$260.00**

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A GOOD electrical connection between the ground rod and the grounding wire is essential for a reliable ground. Corrosion at this contact area can be caused by electrolytic action due to combining dissimilar metals in the presence of moisture.

When a copper ground wire is clamped to a Copperweld Ground Rod the contacts are copper to copper—there are *no* dissimilar metals in contact—and *no* electrolytic corrosion.

The economical method of protecting this vital contact area from electrolysis is to specify non-rusting Copperweld Ground Rods and Clamps thus assuring NO DISSIMILAR METALS IN CONTACT.

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GROUND RODS AND CLAMPS

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The line includes both *direct and alternating current* ammeters, microammeters, milliammeters, voltmeters, millivoltmeters, single *and polyphase* wattmeters, frequency meters and pyrometers.

Long scales, exceptionally high accuracy and illuminated dials (if ordered) are some of the outstanding features of these instruments.

Complete listings and technical details are given in Catalog AE-48-a, *which will gladly be sent on request.*

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The IRC Resistance Engineering Data Bulletins contain the results of many years of specialized experience. They have been classified and prepared to bring exact needed engineering information to assure selection of the *right* resistor for any job. Please ask for them by number.

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2—Metallized Type Resistors: Insulated ½, 1 and 2 watts; high frequency; high range; high frequency power resistors; high voltage power resistors.

3—Insulated Wire Wound Resistors: Type BW from ½ to 1 and 2 watts; Type MW, 5 to 20 watts.

4—Power and Precision Wire Wound Resistors: Power types from 10 to 200 watts, fixed and adjustable types, in wide variety of shapes, mountings, etc. Inductive and non-inductive. 14 Precision types to as close as 1/10 accuracy.

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Fully self-contained. Portable. Removable slip-off cover. Serves as capacity bridge, resistance bridge, insulation resistance tester, vacuum-tube voltmeter, voltmeter (0–600 v.), millivoltmeter (0–60 mv.), milliammeter (0–60 ma.), variable power supply (15–600 v.), etc.

If you use condensers of any type, you should have this dependable yardstick for gauging their true quality. The AEROVOX Capacity & Resistance Bridge, despite its low price of $35.75, is a remarkably precise instrument, with high-grade meter in place of usual neon lamp.

Measures capacity, leakage, power factor, insulation resistance and other characteristics. Serves as vacuum-tube voltmeter, power supply, various meters, etc.

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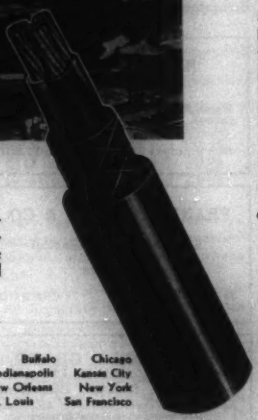

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Employment Bulletin

Engineering Societies Employment Service

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the three offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

ELECTRICIAN, 38, married; 18 yrs maintenance, oprn, constr on pwr plants, substations, mfg plants; also 4 yrs So. Am. mining exper. Location immaterial, available immed; salary secondary, but desires permanent pos. E-533.

B.S.E.E., '38, Univ of Ala, 23, single, Tau Beta Pi, honor student. Desires permanent pos in elec mfg or util. Some exper. Location and salary secondary to opportunity. Now employed. E-534.

B.E.E., NYU '39, 23, single. Location, East or So. Interested indus elec eqpt, jr engr. Pos with opportunity important, salary secondary. Available immed. E-535.

B.S.M.S. in E.E., age 34, married; 2 yrs substation des, 6 yrs instructor in elec engg, 2 yrs sales engr. Desires pos in engg, devpmt or teaching. Available immed. E-536.

B.S.E.E., Northeastern Univ, 1935, 27, single; 4 yrs instal and service elec and refrigerating machy; one yr repair tel eqpt. Desires pos leading to devpmt or application engg. E-537.

E.E., single, 25, HKN, employed; 2 yrs exper in mfr of small motors and applications, dis and special machy des, prod control, cost estimating; 1½ yrs radio test. Available immed. E-538.

E.E., Lafayette Col, 1939, 21, single. Desires pos in pub util or concern mfg elec eqpt. Pwr preferred. Exper primary requisite; salary and location secondary. Available immed. E-539.

B.S.E.E., M.S.E.E., Tau Beta Pi, 28, married. Exper in cost engg, elec des and elec instal in hydro-elec projects. Aptitude, training and exper in math computations. Location immaterial. E-540.

B.E.E., NYU, 1939, single, 23. Eta Kappa Nu. High scholastic record. Desires pos jr engr with advancement, location immaterial, salary secondary, available immed. E-541.

B.S.E.E., '36, single, 23; 2 yrs specification writer and draftsman on condensers; 6 mos testg engr on projectors. Desires pos mach or pwr fields. Location immaterial. E-542.

ELEC ENGR, married, B.S.E.E. Univ Cal 1924; 15 yrs exper central station and indus des, constr and maintenance. Accustomed to full responsibility. E-543-372-C-2-San Francisco.

B.E.E., Rensselaer Poly Inst, '39, single, desires sales engg or instal engg leading to sales engg; Albany or vicinity. Has car, will travel. E-544.

MSEE, advanced work 2 excellent schs; NY license, married; 10 yrs broad and intensive teaching, organizing and indus exper in pwr and com; desires opportunity in teaching, organizing, tech investigation. E-545.

GRAD B.S.E.E., 1934, married, 28; 2½ yrs exper in meters, relays, overhead and underground maintenance. Air conditioning and refrigeration technician. Diesel training. Desires pos with advancement. E-546.

ELEC ENGR, Univ grad 1910, desires pos with pub util co serving one or more cities. Exper largely on pwr stations and substations. Can supervise both oprn and devpmt. E-547.

E.E. with 2 yrs grad work in com; 10 yrs in responsible direction of Army's research and devpmt in com. Wishes commercial connection where this exper would be useful. E-548.

ASST MGR OR PROD ENGR, proved ability, 36, successful in handling labor and plant problems, inventive ability; 10 yrs varied indus exper. B.S. Poly Inst of Bklyn. E-549.

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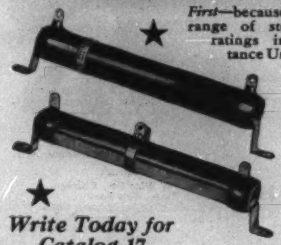

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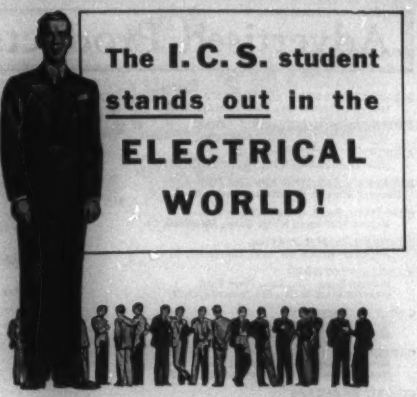

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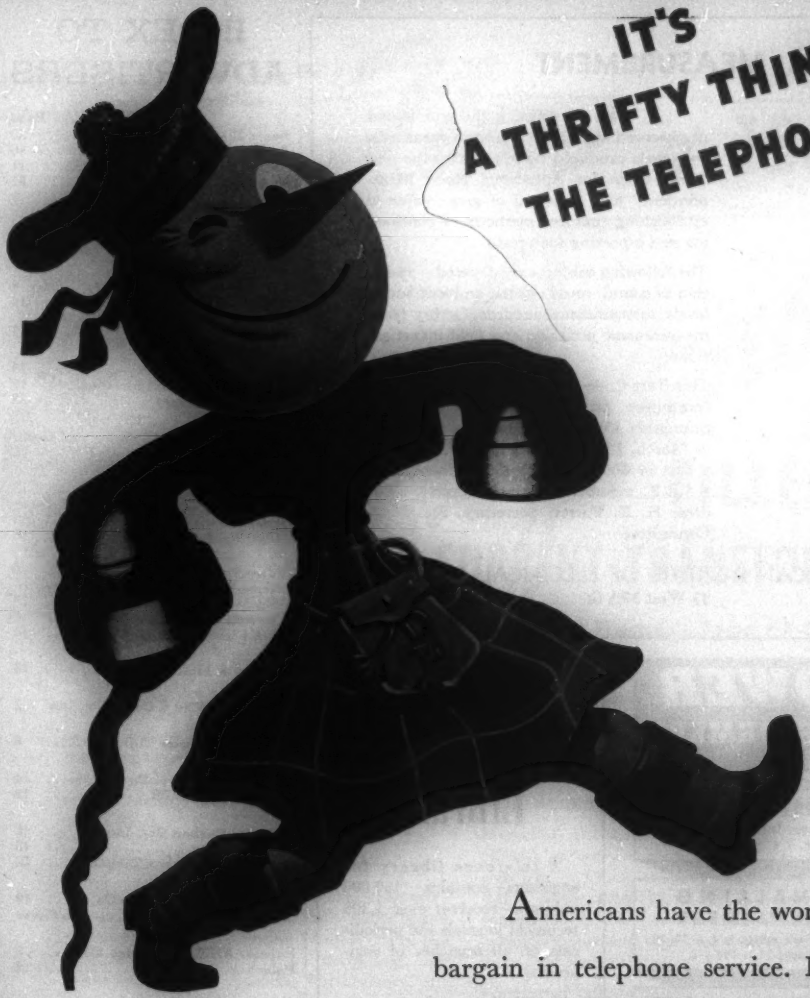

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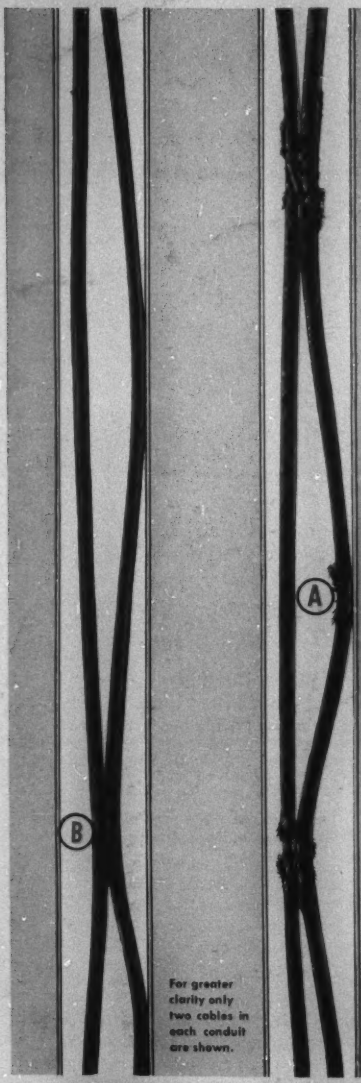

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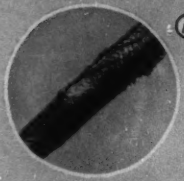

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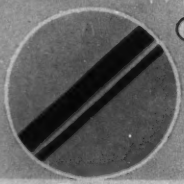

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